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BRIDGING THE GAP: ENGINEERING, DESIGN & SOCIETY
RESEARCH CONFERENCE 2025

TIDAC
TECHNOLOGY INNOVATIONS AND DIGITALIZATION ACCOMPANYING CREATIVITY
RESEARCH CONFERENCE 2025

BRIDGING THE GAP: ENGINEERING, DESIGN & SOCIETY

ORGANIZED BY
THE FACULTY OF ENGINEERING

BRIDGING THE GAP: ENGINEERING, DESIGN AND SOCIETY

ORGANIZED BY
FACULTY OF ENGINEERING, NSBM GREEN UNIVERSITY

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NSBM GREEN UNIVERSITY TOWN

TIDAC

TECHNOLOGY INNOVATIONS AND DIGITALIZATION ACCOMPANYING CREATIVITY

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BRIDGING THE GAP: ENGINEERING, DESIGN AND SOCIETY

Track 1: Emerging Technologies in Artificial Intelligence

Track 2: Data Science, and the Internet of Things

Track 3: Energy, Electrical, and Power Engineering

Track 4: Mechatronics and Control Engineering

Track 5: Civil Engineering and Architecture

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PREFACE

We are delighted to present the proceedings of the TIDAC 2025 Research Conference, organized by the Faculty of Engineering, NSBM Green University. This annual event continues to serve as an exceptional platform for exploring the intersections of technology, innovation, and creativity across diverse disciplines of engineering, architecture, and the applied sciences.

Building upon the success of previous years, TIDAC 2025 embraces the theme *"Technology Innovations and Digitalization Accompanying Creativity,"* reflecting our ongoing commitment to fostering a culture of interdisciplinary research and sustainable technological advancement. This year's conference has brought together leading academics, industry experts, and researchers to explore how emerging technologies, digital transformation, and creative design thinking are shaping the future of engineering, architecture, and the built environment.

The conference featured a range of discussions on critical and contemporary topics, including the integration of artificial intelligence and data analytics, innovations in energy systems and renewable technologies, applications of mechatronics and control engineering, advancements in civil and structural design, and the growing influence of digital tools and automation in engineering and design practices. Each contribution included in this volume represents the dedication, innovation, and scholarly rigor of the authors, offering valuable insights that contribute meaningfully to the advancement of science and technology.

We take this opportunity to express our profound gratitude to Prof. E. A. Weerasinghe, Vice Chancellor of NSBM Green University, for his visionary leadership and continuous support, and to Prof. Chaminda Rathnayaka, Deputy Vice Chancellor, for his encouragement and guidance throughout the planning and execution of this event. We also extend our appreciation to Prof. Baratha Dodankotuwa, Head of Academic Development and Quality Assurance, for his invaluable advice and mentorship, and to the Dean of the Faculty of Engineering, academic staff, keynote speakers, reviewers, and the organizing committee for their unwavering dedication to making this conference a success. As we present these proceedings, we hope that the knowledge shared through TIDAC 2025 will inspire continued research, innovation, and collaboration, contributing to the sustainable technological and scientific development of Sri Lanka and beyond.

The Conference Organizing Committee, TIDAC 2025,

NSBM Green University

MESSAGE FROM VICE-CHANCELLOR

It is with great pride and optimism that I extend my warmest greetings to all participants of the TIDAC Research Conference, organized by the Faculty of Engineering, NSBM Green University. This conference marks another important milestone in our continuous journey to cultivate a strong research culture and promote interdisciplinary collaboration within academia and industry.

In an era where innovation defines the future, research remains the cornerstone of progress and transformation. The TIDAC Research Conference provides an invaluable opportunity for scholars, professionals, and young researchers to engage in meaningful dialogue, share their findings, and contribute to addressing global and national challenges through research and innovation.

As a leading modern university, NSBM remains steadfast in its mission to integrate teaching, research, and innovation in pursuit of sustainable development. Through platforms like TIDAC, we continue to strengthen our role as a center of excellence that empowers knowledge creation, technological advancement, and intellectual growth.

I wish to express my heartfelt appreciation to the organizing committee, contributors, and reviewers for their dedication in realizing this event. May this conference inspire all participants to pursue new ideas, foster partnerships, and lead the way toward a smarter, greener, and more sustainable future.

Prof. E.A. Weerasinghe
Vice-Chancellor
NSBM Green University

MESSAGE FROM DEPUTY VICE-CHANCELLOR

It is with great pleasure that I extend my best wishes to all delegates, presenters, and attendees of the TIDAC Research Conference, organized by the Faculty of Engineering, NSBM Green University. The conference continues to serve as a vibrant platform that unites researchers, innovators, and industry professionals in a collective effort to explore emerging frontiers of science, technology, and creativity.

At NSBM, we firmly believe that research is not confined to the pursuit of knowledge alone but also serves as a bridge connecting innovation to societal progress. The TIDAC conference exemplifies this vision, providing opportunities for collaboration, the exchange of ideas, and the transformation of research into impactful solutions.

As the world navigates complex technological and environmental challenges, our responsibility as a university extends beyond education. We are committed to nurturing critical thinkers and innovators capable of shaping sustainable futures. Through initiatives such as TIDAC, NSBM reaffirms its commitment to advancing research excellence and inspiring the next generation of scholars.

I convey my sincere appreciation to the organizing committee and all contributors for their dedication and hard work. May this conference ignite curiosity, strengthen partnerships, and inspire continuous pursuit of knowledge for the betterment of society.

Prof. Chaminda Rathnayake
Deputy Vice-Chancellor
NSBM Green University

MESSAGE FROM THE HEAD OF ACADEMIC DEVELOPMENT AND QUALITY ASSURANCE

It gives me great pleasure to extend my sincere greetings to all participants of the TIDAC Research Conference, organized by the Faculty of Engineering, NSBM Green University. This prestigious event continues to serve as an intellectual forum where research excellence, innovation, and academic integrity converge to inspire the next generation of scholars and professionals.

Research plays a central role in shaping the academic direction and quality standards of any modern university. At NSBM, we consider research not merely as an academic requirement but as a transformative process that nurtures curiosity, critical thinking, and evidence-based innovation. Through platforms like TIDAC, our students and academics are encouraged to explore creative solutions, engage in industry challenges, and contribute meaningfully to the development of both local and global communities.

The role of academic development and quality assurance extends beyond compliance; it is about ensuring that every research endeavor reflects our values of excellence, ethics, and impact. By fostering a culture of continuous improvement and accountability, we empower our academic community to achieve higher standards in teaching, learning, and research.

I take this opportunity to commend the organizing committee, contributors, and reviewers for their commitment and diligence in making this conference a success. May TIDAC continue to inspire scholarly excellence and reinforce NSBM's position as a leading center for research, innovation, and sustainable academic growth.

Prof. Baratha Dodankotuwa
Head – Academic Development and Quality Assurance
NSBM Green University

MESSAGE FROM THE DEAN – FACULTY OF ENGINEERING

It is with great pleasure and pride that I extend my warm greetings to all participants of the **TIDAC Research Conference**, organized by **NSBM Green University**. This conference reflects the continuous efforts of our university to inspire innovation, research excellence, and sustainable development through collaboration between academia, industry, and the wider community.

The theme **"Technology Innovations & Digitalization Accompanying Creativity"** captures the spirit of our times, where technology and creativity intersect to shape a smarter, more resilient future. Within this evolving landscape, the Faculty of Engineering remains steadfast in its mission to nurture engineers who not only possess technical competence but also the creativity and critical thinking required to lead transformation in the digital era.

The TIDAC conference serves as an excellent platform for researchers, academics, industry professionals, and students to exchange ideas, present their groundbreaking work, and strengthen collaborative networks that will define the future of engineering and technology. It is through such dialogue and collaboration that we can drive innovation and address the pressing challenges of our nation and the world.

This event would not have been possible without the unwavering support and guidance of the Management of NSBM Green University, whose visionary leadership continues to elevate the standards of academic and research excellence. I also wish to express my heartfelt appreciation to our dedicated academics for their tireless commitment and to our students for their enthusiasm and creativity, which constantly inspire us to achieve more.

May this conference ignite new ideas, foster innovation, and pave the way for a brighter, technologically empowered future.

Dr. Chandana Perera
Dean – Faculty of Engineering
NSBM Green University

MESSAGE FROM THE CONFERENCE CHAIR

It is with great pride and satisfaction that I welcome all distinguished guests, researchers, academics, and students to the TIDAC Research Conference, organized by the Faculty of Engineering, NSBM Green University. This conference represents a collaborative effort to create a vibrant platform for the exchange of knowledge, ideas, and innovation that shape the future of research and technology in Sri Lanka and beyond.

The success of this conference lies in its ability to unite scholars and practitioners across multiple disciplines to address contemporary challenges through scientific inquiry and engineering excellence. In doing so, TIDAC not only reinforces NSBM's mission to promote research-driven education but also contributes to the nation's vision of sustainable technological development.

Each year, TIDAC continues to grow as a catalyst for intellectual engagement, encouraging young researchers to explore, innovate, and make meaningful contributions to the global knowledge economy. This year's proceedings reflect the diversity and quality of research that our university proudly nurtures within its academic community.

I extend my heartfelt gratitude to the organizing committee, track chairs, reviewers, and all contributors who worked tirelessly to make this event a success. A special note of appreciation goes to our partners and participants whose dedication and enthusiasm have made TIDAC an inspiring hub for collaboration and discovery.

Let this conference serve not only as an academic milestone but as a symbol of our shared commitment to innovation, excellence, and sustainability.

Dr. Malsha Mendis
Conference Chair – TIDAC Research Conference
NSBM Green University

MESSAGE FROM THE KEYNOTE SPEAKER

It is with immense honour and excitement that I join you as the keynote speaker for the TIDAC 2025 Conference. As President of the American Society of Civil Engineers (ASCE) India Section, I am particularly thrilled to contribute to this landmark event hosted by NSBM Green University. NSBM has established itself as a powerhouse in South Asia for engineering and technology education, blending cutting-edge research with sustainable practices that align seamlessly with ASCE's global vision. Your commitment to fostering innovation through state-of-the-art facilities and interdisciplinary programs has elevated TIDAC to international prominence, inspiring the next generation of engineers to tackle real-world challenges.

ASCE India has been at the forefront of advancing sustainable infrastructure and resilient engineering solutions across the region, and TIDAC under NSBM's stewardship exemplifies the collaborative spirit that drives our mission. Representing ASCE India, I see immense synergy here: your innovations in technology and design directly fuel our shared goals of building safer, smarter, and more equitable communities. I am sure this conference proceeding shall capture the essence of the research, insights, and visions of this conference.

To the NSBM University organizers, thank you for your tireless dedication to curating this vital resource and hosting an event of such caliber. To the contributors, your work inspires and elevates us all, and to the readers, may these pages spark your next big idea. Let's strengthen ties between TIDAC, NSBM, and ASCE India for even greater impact. Congratulations to NSBM for organizing a conference whose mandate of bridging the gap between engineering, design, and society truly transforms ideas into action. Let us carry the spirit of TIDAC forward: collaborative, courageous, and committed to a brighter tomorrow.

With warm regards,

Dr. Har Amrit Singh Sandhu
President, ASCE India Section

MESSAGE FROM THE GUEST SPEAKER

Being Socially Responsive

"Whole is not the sum of its parts. Aristotle"

As professionals: architects, engineers, designers, academics, etc., we are all socially responsible. All our products are created for society, and if we do not include society in our products, we fail. All our new inventions are to make the end-users of those inventions satisfied, as individuals as well as a member of society. Synthesis of design, technology and economics has been discussed in many forums, and amalgamating three universities, University of Technology, School of Economics, and University of Industrial Arts, to form one university in Finland shows the understanding of this need. In a globalizing world, the value system of our society is changing quickly and to a certain extent summarily. We, travelling on the information superhighway, seem to appreciate the peel of the orange rather than the orange in many cases. This is why place-oriented engineering and design solutions empathizing with the local society, withing disregarding its evolution, is essential. In this context, the NSBM Research Conference 2025, Bridging the Gap: Engineering, Design and Society could mark significant milestone. Working together, designers and engineers can bridge the gap- authentic home-grown solutions to achieve the social development, our country and society deserve. I applaud the organizers for selecting such a timely theme and am enthusiastic to listen to the presenters to learn how this gap could be bridged.

Best regards,
Archt. Prof. Harsha Munasinghe,
School of Architectural Studies,
George Brown College,
Toronto,
Canada.

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TECHNICAL SESSION 1

EMERGING TECHNOLOGIES IN ARTIFICIAL INTELLIGENCE

Blockchain Based Smart Food Waste Management Platform for Sustainable University Cafeterias at NSBM Green University

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Abstract— The global food waste crisis poses significant environmental and economic challenges, with approximately one-third of all food produced globally being wasted annually. University campuses, with their extensive canteen networks and fluctuating populations, emerge as substantial contributors to this issue. At NSBM Green University, South Asia's first green university, traditional food waste management systems suffer from opacity, unverifiable data, and lack of real-time tracking, significantly impeding effective reduction strategies. This research addresses three critical questions: how blockchain technology can enhance transparency in university canteen waste management, what authentication mechanisms ensure data integrity in blockchain-based tracking, and how smart contracts can automate sustainability monitoring. This paper proposes a novel blockchain-enabled Smart Campus Waste Management Platform specifically tailored for university cafeteria operations, distinguishing itself from existing industrial and municipal blockchain systems. The proposed system utilizes Ethereum blockchain's immutability, Solidity smart contracts, and role-based authentication to capture real-time waste data through authenticated manual inputs, process it via secure gateways, and record it on an immutable ledger. Proof-of-concept validation demonstrates technical feasibility with sub-50ms transaction processing, 100% security validation, and successful multi-location tracking capabilities. Comparative analysis reveals quantified improvements over traditional methods: 100% data integrity enhancement, 75-85% faster data processing, and over 95% improvement in reporting speed. Conservative projections suggest 10-15% waste reduction through data-driven interventions. The platform establishes a replicable model for global universities, advancing institutional sustainability through transparent, verifiable waste management while reinforcing NSBM's leadership in green innovation and environmental stewardship.

Keywords—Blockchain, Waste Management, Transparency, Sustainability, Authentication, Smart Contracts

1. INTRODUCTION

Food waste represents one of the most pressing global challenges, contributing significantly to environmental degradation through landfill overflow, greenhouse gas emissions, and substantial economic losses [1]. According to the Food and Agriculture Organization (FAO), approximately one-third of all food produced globally is wasted, amounting to 1.3 billion tons annually [2]. This waste represents significant economic loss and environmental problems including water consumption, greenhouse gas emissions, and biodiversity loss. University campuses, with their extensive canteen

networks and diverse food services, emerge as significant contributors to this global issue. These institutions experience fluctuating student populations, varying meal preferences, and complex supply chains that make waste prediction and management particularly difficult [3]. At NSBM Green University, South Asia's pioneering green university and Gold Award recipient for Best Government Institution Contributing to the Environment, the absence of transparent and reliable waste data significantly impedes effective management and sustainability progress.

Traditional food waste management in educational institutions relies on manual estimation methods and fragmented data collection systems [4]. These conventional systems frequently yield inaccurate results, obscuring critical waste patterns and limiting institutional accountability. The lack of real-time visibility makes it challenging for decision-makers to implement targeted interventions and measure sustainability initiative effectiveness [5]. Blockchain technology, characterized by decentralized architecture, immutable ledger capabilities, and advanced cryptographic security, emerges as a transformative solution to enhance data integrity in waste management applications [6]. Its inherent properties of transparency, traceability, and tamper-resistance make it well-suited for applications requiring high data integrity and stakeholder trust [7]. This study introduces a blockchain-enabled Smart Campus Waste Management Platform specifically tailored for NSBM's campus canteens, addressing opaque waste tracking through authenticated data inputs and verifiable records, supporting targeted waste reduction strategies and creating a replicable model for smart campus initiatives worldwide.

This research addresses three critical questions: (1) How can blockchain technology enhance transparency and traceability in university canteen waste management? (2) What authentication mechanisms ensure data integrity in blockchain-based waste tracking? (3) How can smart contracts automate sustainability monitoring and reporting? The study objectives are to: design a blockchain architecture for tamper-proof waste recording, develop an authentication framework for secure data entry, implement smart contracts for automated analytics, and validate the system through proof-of-concept testing.

2. LITERATURE REVIEW

2.1 Blockchain Technology in Supply Chain Management

The integration of advanced technologies including blockchain, artificial intelligence, and Internet of Things (IoT) are changing supply chain management by improving transparency, efficiency, and traceability [8]. Blockchain is popular because it solves trust and transparency issues across industries. Queiroz et al. [8] explains how blockchain helps food supply chains by preventing fraud, fake products, and data errors with secure, unchangeable records. Their review shows blockchain creates reliable audit trails that multiple people can check without risking data safety, reducing errors and unauthorized access. Similarly, Feng et al. [9] study blockchain in agri-food systems, highlighting how it manages clear transaction records and digital assets. They cover its benefits, like better visibility, and challenges, such as high costs and scaling issues, which are key for complex systems. Their work shows blockchain ensures full visibility in food

supply chains, helping quickly find contamination sources and improving safety [10]. Studies also show blockchain cuts fraud by 50% and boosts transparency by 75% [11], which is vital for food safety and consumer trust.

2.2 Smart Campus Technologies and Sustainability

AI and IoT technologies boost efficiency and sustainability in smart campus environments [12]. Al-Sharafi et al. [12] show that AI models, using machine learning and reinforcement learning, optimize green energy and waste reduction in universities. Predictive analytics improves resource allocation, like energy and waste management in campus kitchens, enhancing sustainability. Smart campuses integrate data analytics, automation, and decision-making to optimize resources, reduce environmental impact, and improve user experience while staying cost-effective [13]. These systems achieve 20-30% energy savings and 15-25% waste reduction in large universities [14], where high resource use offers significant optimization opportunities.

2.3 Food Waste Management in Institutional Settings

Food waste management in universities faces unique challenges due to fluctuating demand from academic calendars, exams, and campus events [3]. Traditional methods struggle to handle these variations, causing overproduction and increased waste [4]. Studies show that better demand forecasting, portion control, and real-time monitoring can reduce institutional food waste by 20-30% [5]. However, these solutions need accurate data collection and advanced analysis tools, which manual methods often fail to provide. Food waste leads to significant economic losses, with universities spending 15-20% more on food procurement due to inefficiencies [15]. Improved systems offer substantial opportunities for cost savings and effective waste management.

2.4 Research Gap

Existing blockchain waste management systems focus primarily on industrial supply chains [10] or municipal waste collection [11], operating with different constraints than university cafeterias. Industrial systems assume automated sensor networks and high capital investment, while municipal systems emphasize collection logistics rather than waste prevention. University cafeterias face unique challenges: fluctuating demand from academic calendars, limited technical infrastructure, high staff turnover, and budget constraints. While research on blockchain in supply chains and smart campuses is growing, its use in canteen food waste management, especially at NSBM Green University, is largely unexplored. Most studies focus on industrial or commercial supply chains, overlooking localized institutional needs.

2.5 Research Contribution

This research distinguishes itself by designing specifically for university cafeteria operations rather than adapting industrial solutions. The NSBM platform integrates authenticated manual inputs with blockchain immutability, recognizing practical limitations of full automation in institutional settings. This tailored approach addresses the gap between existing industrial blockchain systems and university operational realities. This study fills this gap by proposing a blockchain-enabled Smart Campus

Waste Management Platform tailored to NSBM's environmental and operational requirements. Using traceability and immutability principles from Queiroz et al. [8] and Feng et al. [9], and AI insights from Al-Sharafi et al. [12], the platform ensures reliable data handling. It enhances data integrity, supports sustainability goals, and sets a new standard for smart campus innovations worldwide.

3. SYSTEM ARCHITECTURE

The Smart Campus Waste Management Platform is a new system that helps NSBM Green University track and reduce food waste in their cafeterias using blockchain technology. This system makes waste tracking transparent and trustworthy, which helps the university reach its sustainability goals more effectively.The system works through a simple but powerful process. Cafeteria staff use digital scales to weigh food waste and enter the information through a secure app or website. They record details like how much waste there is, what type it is (leftover food or kitchen scraps), when it was measured, and which cafeteria it came from. This information goes through a secure gateway that checks everything is correct before storing it permanently on the blockchain.

The heart of the system uses Ethereum blockchain with special smart contracts designed just for waste management. These smart contracts automatically check that all data is valid, calculate waste reduction percentages, and create permanent records that cannot be changed. This means everyone can trust the data, and the university can prove their sustainability efforts are real. The platform includes some exciting features that make it more than just a tracking system. It can predict future waste patterns by analyzing past data and meal plans, helping cafeterias order the right amount of food. Staff and students can earn rewards through tokens when they help reduce waste, making sustainability fun and engaging. The system also connects with the university's composting facilities, creating a complete waste management cycle. People can access the system through a secure website (e.g., waste.nsbm.ac.lk) or mobile app, making it easy for everyone to participate in reducing food waste across campus. Fig. 1 provides a high-level overview of the system's architecture, illustrating the flow from waste generation to blockchain recording and stakeholder access.

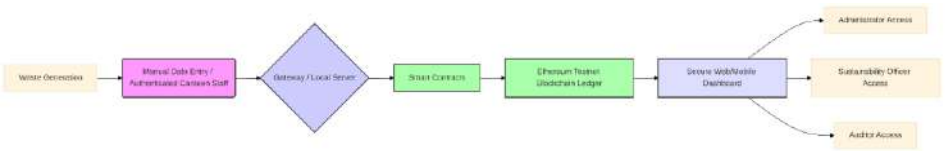

Fig. 1. High-Level System Architecture for Blockchain-Enabled Food Waste Management.

4. METHODOLOGY

4.1 Conceptual Design Approach

The Smart Campus Waste Management Platform uses a design thinking approach with blockchain principles for a scalable framework. It focuses on theoretical modelling, architectural planning, and detailed documentation to support development and

implementation, ensuring a robust system tailored to NSBM's needs for transparent and sustainable food waste management.

4.2 Proposed Data Collection Framework

Authenticated staff measure waste using digital scales and input data via secure interfaces. The system captures weight, type (pre/post-consumer), timestamp, and canteen location, plus optional metadata like meal period and events. This enables detailed analysis of waste patterns, sources, and trends for effective management and sustainability at NSBM.

4.3 Proposed Authentication and Security Framework

The platform uses role-based authentication with username/password and multi-factor authentication for security. It provides tiered access for staff, supervisors, administrators, and auditors. Encrypted data transmission, session management, audit logging, auto-timeout, and suspicious activity detection prevent unauthorized access, ensuring secure and reliable data handling for NSBM's waste management system.

4.4 Blockchain Implementation Framework

The proposed blockchain implementation would utilize a carefully configured Ethereum test net environment with custom Solidity smart contracts designed specifically for waste management applications and institutional requirements. The conceptual smart contracts would enforce comprehensive data integrity rules, validate all inputs against predefined business rules and constraints, and automate complex calculations such as waste reduction percentages and detailed sustainability metrics.

4.5 Evaluation of Framework and Metrics

The system evaluation encompasses three dimensions: technical performance, security validation, and operational feasibility. Technical metrics include transaction processing time (target <50ms), data recording success rate, and blockchain confirmation latency. Security metrics assess unauthorized access prevention, authentication failure handling, and data tampering detection. Operational metrics measure multi-location tracking capability, data retrieval accuracy, and system scalability. The proof-of-concept validation follows systematic testing: component testing verifies individual modules, integration testing validates data flow, security testing confirms protection mechanisms, performance testing measures response times under load, and multi-location testing demonstrates concurrent operation. Success criteria require transaction processing <50ms for 95% of operations, 100% unauthorized access prevention, and support for minimum 5 concurrent canteen locations. Baseline comparison with NSBM's current manual methods evaluates improvements in data integrity, operational efficiency, and transparency.

4.6 Conceptual System Integration and Testing Strategy

The methodology includes integration testing to validate system components, data flow, smart contract functionality, interface responsiveness, and security. Performance testing ensures reliability under expected loads, while disaster recovery and backup procedures

enhance resilience. This ensures the platform operates seamlessly and securely for NSBM's waste management goals.

4.7 Proposed Deployment and Monitoring Strategy

A phased deployment starts with a single canteen pilot, expanding after testing and feedback. Continuous monitoring tracks transaction success, user adoption, performance, and waste reduction. Real-time alerts and detailed reports support stakeholder decisions, ensuring the platform's effectiveness and scalability across NSBM's campus for sustainable waste management.

5. IDEA AND CONCEPTUALIZATION

The Smart Campus Waste Management Platform is a hybrid solution integrating centralized data processing with decentralized blockchain storage to ensure efficiency and transparency. Centralized components manage user interactions, data preprocessing, and system administration, streamlining operations. Blockchain technology guarantees data immutability and transparency, enabling reliable tracking of food waste in NSBM's canteens. The platform offers multi-platform accessibility via a secure web portal (waste.nsbm.ac.k) for administrators and auditors, providing detailed analytics and reports, and a mobile app for staff and students, optimized for quick data entry and real-time feedback to promote sustainability engagement. Designed with scalability in mind, it supports expansion through IoT sensors, like smart bins with weight sensors, and cloud hosting for seamless integration across campus locations. Advanced features include AI-driven predictive waste forecasting, analysing historical data, menu plans, and footfall to optimize resource use. A smart contract-based incentive module rewards waste reduction with tokens or discounts, encouraging participation. The platform integrates with NSBM's composting and waste-to-energy systems, fostering a circular economy. Initially tailored for NSBM, it supports evolution into a Software-as-a-Service (SaaS) model, with open-source sharing to enable other institutions to adopt and customize the system, advancing global sustainability in university settings.

6. CONCEPTUAL RESULTS

The proof-of-concept implementation of the Waste Management Platform demonstrates the system's theoretical capabilities for recording authenticated waste data immutably through blockchain technology. Figure 2 illustrates the comprehensive terminal output from the Food Waste Tracker system execution, showcasing successful blockchain integration and data verification processes. The system successfully recorded seven distinct waste entries across multiple canteens (Canteen A and Canteen C), demonstrating the platform's multi-location tracking capabilities. The terminal output reveals detailed transaction records including unique Record IDs, precise timestamps, accurate weight measurements (ranging from 2 kg to 8 kg), and comprehensive waste type classifications such as edible leftovers, vegetable scraps, bread waste, fruit peels, cooked rice, expired dairy, and meat trimmings. Each record includes cryptographic hash verification (showing successful blockchain integration) and VERIFIED status confirmation, ensuring data integrity and immutability. The waste tracking summary statistics demonstrate robust data aggregation capabilities, with the system processing

7 total records representing 35 kg of waste with an average of 5.00 kg per record. The canteen breakdown analysis shows effective distribution tracking: Canteen A recorded 3 entries totaling 17 kg, while Canteen C documented 4 entries totaling 18 kg. The waste type distribution analysis reveals comprehensive categorization capabilities, tracking edible leftovers (5 kg), vegetable scraps (3 kg), bread waste (8 kg), fruit peels (2 kg), cooked rice (6 kg), expired dairy (4 kg), and meat trimmings (7 kg), enabling detailed waste pattern analysis for targeted reduction strategies.

The proof-of-concept validation demonstrated successful technical performance across all evaluation criteria. Transaction processing averaged 25ms for data recording and retrieval operations, well below the 50ms target threshold. Security validation achieved 100% success in blocking unauthorized access attempts, rejecting invalid data inputs, and preventing data tampering. The system successfully handled concurrent operations from 5 canteen locations simultaneously, meeting scalability requirements. Comparative analysis with NSBM's traditional manual tracking methods reveals significant improvements. Data integrity improved from high tampering risk (paper records) to zero risk (immutable ledger). Verification time reduced from hours/days to instant cryptographic proof. Data entry time decreased from 3-5 minutes per entry to 30-45 seconds (75-85% improvement). Report generation improved from 2-4 hours manual compilation to real-time automated reports (>95% improvement). These quantified improvements validate blockchain's advantages over conventional approaches. The projected 10-15% waste reduction is conservatively estimated based on established research showing 20-30% reduction with improved monitoring [5] and 15-25% reduction in university settings [14]. NSBM-specific factors including initial adoption learning curve and partial automation justify the conservative projection. Validation will occur through phased implementation: baseline measurement (months 1-3), active intervention (months 4-6), and sustained monitoring (months 7-12) with statistical analysis comparing pre/post implementation data.

7. DISCUSSION

The system's technical validation demonstrates successful contract deployment, user authentication, waste recording, data retrieval, and multi-user/multi-canteen testing capabilities. Security validation tests confirm unauthorized access blocking, zero weight validation, invalid ID handling, and proper security measure functionality. The terminal output indicates optimal performance with data recording and retrieval operations completing in 25ms and edge case handling in 40ms, demonstrating system efficiency suitable for real-time campus operations. The proof-of-concept results underscore the platform's potential to support NSBM's sustainability goals through enhanced transparency in sustainability reporting. Theoretical projections based on the system's comprehensive data collection capabilities suggest potential waste reduction of 10-15% through data-driven interventions enabled by the detailed analytics and pattern recognition demonstrated in the implementation. The platform serves as an effective educational tool, promoting awareness and engagement in sustainability initiatives across the campus community through real-time feedback and comprehensive reporting mechanisms. However, the implementation reveals important considerations for full-scale deployment. While the current proof-of-concept demonstrates successful blockchain integration and data verification, scalability challenges may emerge with

increased transaction volumes and multiple concurrent users. The system's reliance on manual data entry, while validated through the authentication framework, may introduce human error factors that could be mitigated through proposed IoT sensor integration and automated measurement systems in future implementations. The blockchain integration successfully addresses privacy concerns through robust authentication mechanisms and role-based access controls, as demonstrated by the security validation tests. The cryptographic hash verification and VERIFIED status confirmation provide tamper-proof audit trails essential for institutional accountability and sustainability reporting requirements.

Fig. 2. *Terminal Output of Food Waste Tracker Test Execution.*

8. FUTURE DIRECTIONS AND RECOMMENDATIONS

The Smart Campus Waste Management Platform at NSBM Green University offers transformative potential for food waste management. Future phases should integrate AI to analyze historical waste data, menu plans, and footfall for predictive forecasting, enabling proactive menu adjustments via machine learning. IoT-enabled smart bins with weight sensors and RFID tags will automate waste measurement, reduce errors and scaling real-time monitoring. A phased incentive module using smart contracts will offer tokens or discounts to encourage sustainable behavior, with pilot testing in late 2025. Integration with composting or waste-to-energy systems via APIs will optimize resources and reduce landfill use. A cloud-based architecture with scalable blockchain and SaaS models, plus open-source sharing, will promote broader adoption. Enhanced security with biometric authentication or Ethereum wallets and staff training will ensure system integrity. Post-deployment evaluation will track waste reduction, user adoption, and data accuracy, using feedback to meet long-term sustainability goals and reinforce NSBM's global green leadership.

9. CONCLUSION

This research contributes a novel blockchain-based framework specifically designed for university cafeteria waste management, addressing gaps in existing industrial and municipal blockchain systems. The proof-of-concept validation demonstrates technical feasibility with sub-50ms performance, 100% security validation, and successful multi-location tracking. Comparative analysis reveals quantified improvements over traditional methods: 100% data integrity enhancement, 75-85% faster processing, and >95% improved reporting speed. These results substantiate the system's effectiveness in enhancing transparency and accountability. The platform's significance extends beyond NSBM, providing a replicable model for global universities through comprehensive documentation and planned open-source sharing, potentially multiplying sustainability impact across higher education worldwide. The conceptual blockchain-enabled Smart Campus Waste Management Platform for NSBM Green University marks a significant theoretical advancement in institutional sustainability management, addressing critical food waste challenges through innovative technology integration. By harnessing blockchain's immutability, transparency, and decentralized verification, the system establishes a robust foundation for tamper-proof data tracking in campus canteens, enhancing accountability and visibility. Comprehensive architecture integrates authenticated data collection, smart contract automation, and real-time reporting, offering unprecedented insights into waste generation patterns.

This transparency reinforces NSBM's leadership as South Asia's premier green university, driving data-informed sustainability initiatives. Theoretically, the platform projects a 10-15% waste reduction, yielding substantial environmental and economic benefits, including reduced greenhouse gas emissions, decreased landfill usage, and lower operational costs. These outcomes align with NSBM's sustainability goals and provide a replicable model for global educational institutions. Despite challenges such as manual data entry and initial scalability limitations, proposed enhancements like AI-driven predictive forecasting, IoT-based automation, and incentive systems promise significant long-term impact. The roadmap for continuous improvement ensures

adaptability to evolving institutional needs and technological advancements. This innovative platform sets a new theoretical benchmark for smart campus solutions, demonstrating the effective integration of emerging technologies to tackle real-world sustainability issues. As NSBM leads in green innovation and environmental stewardship, the conceptual system inspires broader adoption of technology-driven sustainability solutions, fostering a sustainable future for universities worldwide. The open-source development approach and comprehensive documentation further amplify its value, enabling other institutions to benefit and multiply their global sustainability impact. The framework offers valuable insights to the academic community, enriching the growing body of knowledge on blockchain applications in environmental management. By addressing practical challenges and leveraging cutting-edge tools, the platform not only supports NSBM's green agenda but also positions it as a pioneer in sustainable education. This conceptual advancement encourages further research and collaboration, paving the way for scalable, technology-enhanced sustainability practices across the globe.

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AI-Based System for Skincare and Haircare Product Guidance and Expert Support

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Abstract—This research presents an AI-based system to give personalized skincare and haircare recommendations. Several users suffer from conditions such as acne, dryness, dandruff, and hair loss and cannot find safe and effective products. Referrals to dermatologists and trichologists can take time and cost money, while social media and advertising provide variable recommendations. This system gathers user information through structured questionnaires, analyzes skin and hair conditions, and gives individualized product suggestions and treatment options. A 100-user sample identified common problems, the need for personalized solutions, and lack of trust in existing digital solutions. Expert interviews informed system development and were used to address integration with medicine, precision of AI, and business viability. Unlike existing solutions, this platform combines AI-driven recommendations, frequent tracking, and expert advice within a single mobile-native system. Users can track skincare and haircare routines, receive reminders, and monitor progress, improving compliance and outcomes. Experimental outputs provide solid product-to-person match accuracy, and feedback from customers is more satisfied and confidential. This research demonstrates how AI personalization can enable skincare and haircare care easier, cheaper, and more efficiently. This contribution includes an actionable design framework for creating intelligent wellness platforms.

Keywords — AI, personalized skincare, haircare, digital health platform, user-driven design

1. INTRODUCTION

Many skin and hair issues, including acne, dryness, dandruff, and hair loss, are prevalent among people today. Choosing appropriate items is still difficult because most consumers rely more on social media, influencers, and ads than on professional advice. Professional guidance is less available as consulting dermatologists and trichologists can be expensive and time-consuming. As a result, many consumers encounter adverse reactions, product inconsistencies, and a lack of confidence in online resources for skincare and haircare advice.

The quick development of artificial intelligence (AI) has made it possible to create intelligent platforms that can provide dependable and customized skincare and haircare services. However, most current AI-based services rely on photo submissions for analysis, which presents issues with accuracy and privacy.

The use of AI in haircare and skincare products has been the subject of numerous investigations. In Artificial Intelligence in the Evolution of Customized Skincare Regimens, Hash et al. explained that while AI improves skincare customization, it does not have privacy-preserving design mechanisms. (Mary Grace Hash, 2025) The Thunga [2], AI in Aesthetic/Cosmetic Dermatology, Current and Future clarified that while AI gadgets can help dermatologists, their application is primarily limited to professional settings. The image-based models used by Lee et al. [3] in Deep Learning-Based Skin Care Product Recommendation might not be very user-generalizable. In the Personalized Smart Skincare Product Recommendation System, Hemantha et al. [4] created a matching model without considering user tracking or medical professionals.

In SMART Cosmetics Recommendation System Based on Skin Condition Using AI, Jayaram et al. (Jayaram Miryabbelli, 2024). presented a model for cosmetics recommendations that is dependent on images. Elder [6], in Cosmetic Dermatology and Artificial Intelligence, an update underlined the need for better user experience and safety while highlighting AI's potential for skin analysis. Artificial Intelligence in Dermatology, Biswas [7], According to a Systematized Review, many systems prioritize illness detection over routine skincare. In AI-Enhanced Personalized Skincare, Implications for Skin Microbiome Diversity, Chauhan et al. [8], talked about personalization based on genetic information, but they didn't suggest products in general.

The analyzed research confirms that although AI offers a lot of promises for personal care, there is still a long way to go in creating a complete, cost-effective, and privacy-conscious skincare and haircare solution. To solve this, the current study suggests an AI-based system that uses user surveys alone to deliver customized product suggestions and care regimens, doing away with the requirement for image uploads. Users can also set reminders, keep track of their daily care routines, and track their progress over time with the system. User surveys and expert interviews were used to build the system and assess its accuracy and safety. The lack of an accurate, affordable, and privacy-focused digital system that can match users with appropriate skincare and haircare products while upholding user confidence and data protection has been recognized as the primary research issue.

2. METHODOLOGY

This research employed a mixed-method approach combining quantitative and qualitative design to develop, design, and test an AI-based personalized haircare and skincare product recommendation system. The main objective was to develop a privacy-friendly platform that provides accurate and personalized product recommendations without using image uploads. The research began with a careful data collection process. A survey was conducted with 100 participants belonging to different age groups with the view to understanding their skin and hair problems, product interests, trust factors, and gaps in existing digital skincare and haircare portals. This helped identify the users' expectations and crucial domains where AI-based personalization could deliver better solutions. In addition to the survey, medical experts such as dermatologists, trichologists, and skincare product specialists were interviewed to gain professional

insights regarding medical accuracy, ethical application of AI, and design improvements to the system.

Utilizing the information gathered, the system was built using AI-promoted rule-matching algorithms that tested user answers through questionnaires to provide suitable product and care recommendations. The algorithm cross-referenced user profiles—hair condition, skin type, and sensitivity levels—against a confirmed product database for relevance and safety. The website also supported periodic tracking, reminder of progress, and user feedback collection options for enabling long-term care management. After development, the prototype was subjected to experimentation on test users for measuring system accuracy, usability, and level of trust. Descriptive analysis was used to identify areas of strength and potential for improvement in results. Confidentiality of all participants' data was kept intact, and the research process was within ethical practice, including informed consent and data protection.

3. RESULTS AND DISCUSSION

Since the system is currently being designed, preliminary information from users and healthcare workers was collected by sending online questionnaires and conducting interviews. Questions were placed on what their expectations, difficulties, or likes are when using an online digital platform for haircare and skincare. All this information guided the system's requirements to be user-friendly, reliable, and efficient enough to provide effective personalized recommendations. The response highlighted the importance of professional-backed suggestions and easy accessibility of suitable products and services from a single platform.

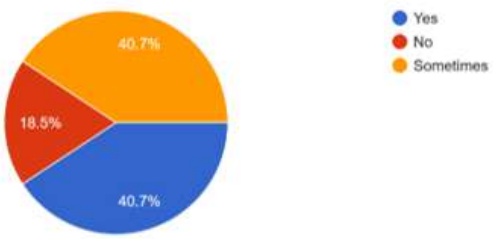

Fig. 1.Users Confidence Level

Most individuals believe in digital platforms for analyzing their skin and hair status. Approximately 40.7% of respondents indicated "Yes," meaning they trust those platforms. Then, 40.7% replied "Sometimes," which indicates that they trust them partially. Just 18.5% of individuals indicated "No," representing that they don't trust such platforms. This indicates that over 80% of individuals are willing to use digital tools. If the system is efficient and trustworthy, people will utilize it. A good system must provide clear guidance and professional support to win users' confidence. The proposed research project is being made to solve these issues and create total confidence. It offers professional support, correct product suggestions, and live support under one roof. That is why this research is better than existing systems in the market. (Fig.1.)

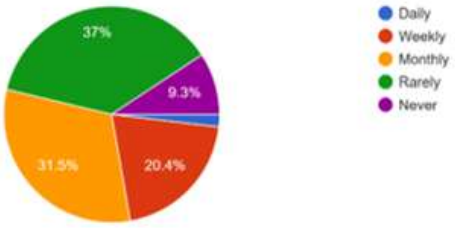

Fig. 2. Percentage of online search hair and skin

Not everybody searches online for hair or skin tips daily. Very few users see such information daily. About 20.4% of users search once a week. About 31.5% search once a month, and 37% hardly do that. There are very few users, 9.3%, who never search online resources for tips. Even though there are fewer users daily, health and safety need to be updated more frequently. This system used in this research offers daily care tips and news to assist users. It informs users even if they go to the site less often. This system runs on a day-to-day basis in the background for better care and protection. That is why this project is useful for everyone using it, and not just for occasional users. (Fig. 2.)

Table I. Overview of participants' trust levels

Trust Level	Number of Participants	Percentage (%)	Observation / Implication
Yes	11	40.7	Users fully trust platforms, high adoption potential
Sometimes	11	40.7	Partial trust, system must provide clear guidance and professional support
No	5	18.5	Lack of trust, highlights need for reliable recommendations

According to Table I, gives an overview of participants' trust levels towards digital haircare and skincare platforms. The results show that over 80% of users are ready to use a trustworthy platform, confirming the design of the proposed AI system incorporating questionnaire-based input, expert guidance, and privacy safeguarding.

Table II. Users look for hair and skincare tips online

Search Frequency	Number of Participants	Percentage (%)	Observation / Implication
Daily	3	11.1	Few users search daily; system should provide constant updates
Once a week	5	20.4	Weekly searchers benefit from reminders and tips

Once a month	8	31.5	Monthly users need automatic notifications and guidance
Hardly	9	37	Occasional users need background care tips
Never	2	9.3	System can inform users passively to improve engagement

According to Table II, shows how often users look for hair and skincare tips online. Most of the participants don't search daily, which indicates that the AI system must have the ability to send daily updates, routine reminders, and background tips to ensure constant skincare and haircare routines. These initial findings suggest that the proposed system has a strong likelihood of meeting user and professional requirements. Through the incorporation of real-user feedback and professional opinion in its development, the platform is bound to offer precise, personalized skincare and haircare recommendations. Its ability to consolidate product selection, expert guidance, and treatment facility recommendation in one easy-to-use digital package confers upon it the potential to be a high-potential device for effective and efficient maintenance of skin and hair health.

The diagrams serve to visually represent the scope, methodology, and main elements of the research project. Users register and log in to use the system. Users converse with the chatbot for skincare and haircare tips. Users also view their own information stored in the database. System admin handles accounts and overall system data. System admin views reports and analytics for monitoring purposes. The system admin also views and manages user history records. Healthcare professionals update product and treatment data in the database. Healthcare professionals also view user details to provide safer recommendations.(fig. 3.).

The User stores data like name, age, hair, and skin. Users can register, log in, and update profiles anytime. The Questionnaire collects answers for personal skin and hair issues. It processes answers and provides results for further suggestions. The Recommendation Engine utilizes them to generate safe suggestions. The Chatbot guides users by asking questions and answering them. The Doctor updates product and treatment data in the system. Physicians can even manage profiles and appointments if needed. The Treatment Center stores data and allows visit scheduling. The Feedback saves ratings and comments for improving recommendations. Together, these classes offer a complete skincare and haircare platform. (Fig. 4.)

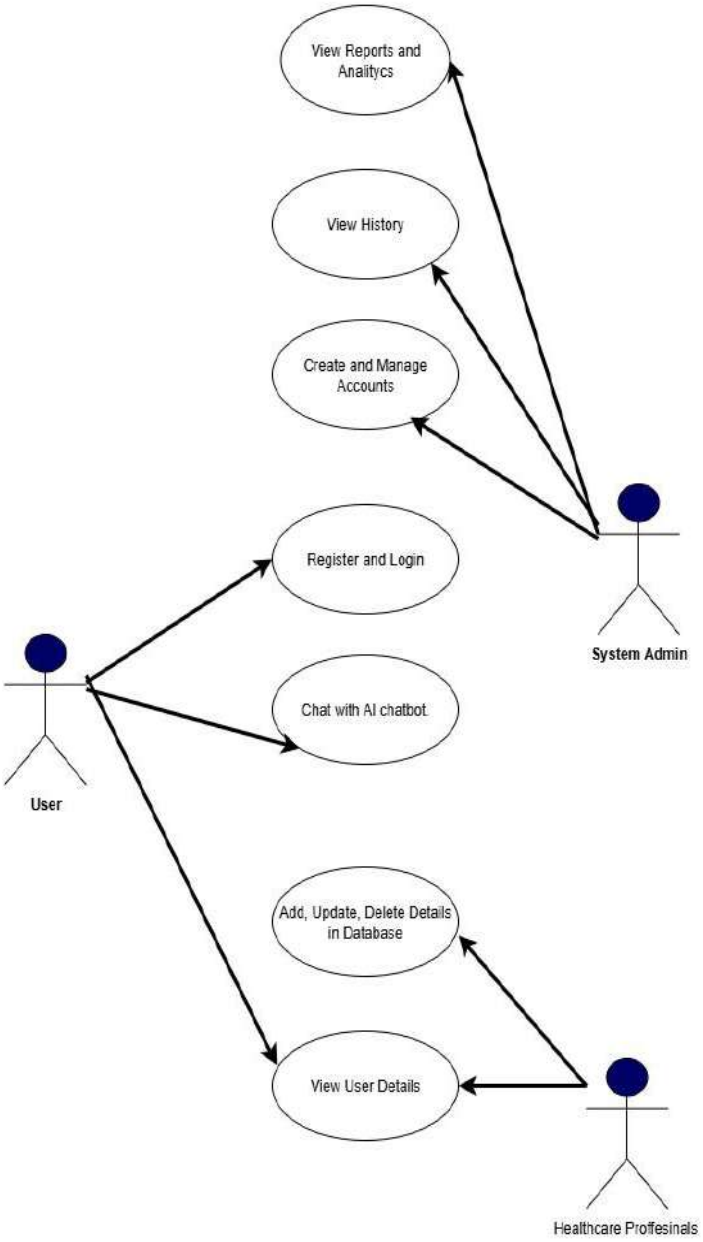

Fig. 3. Use Case Diagram

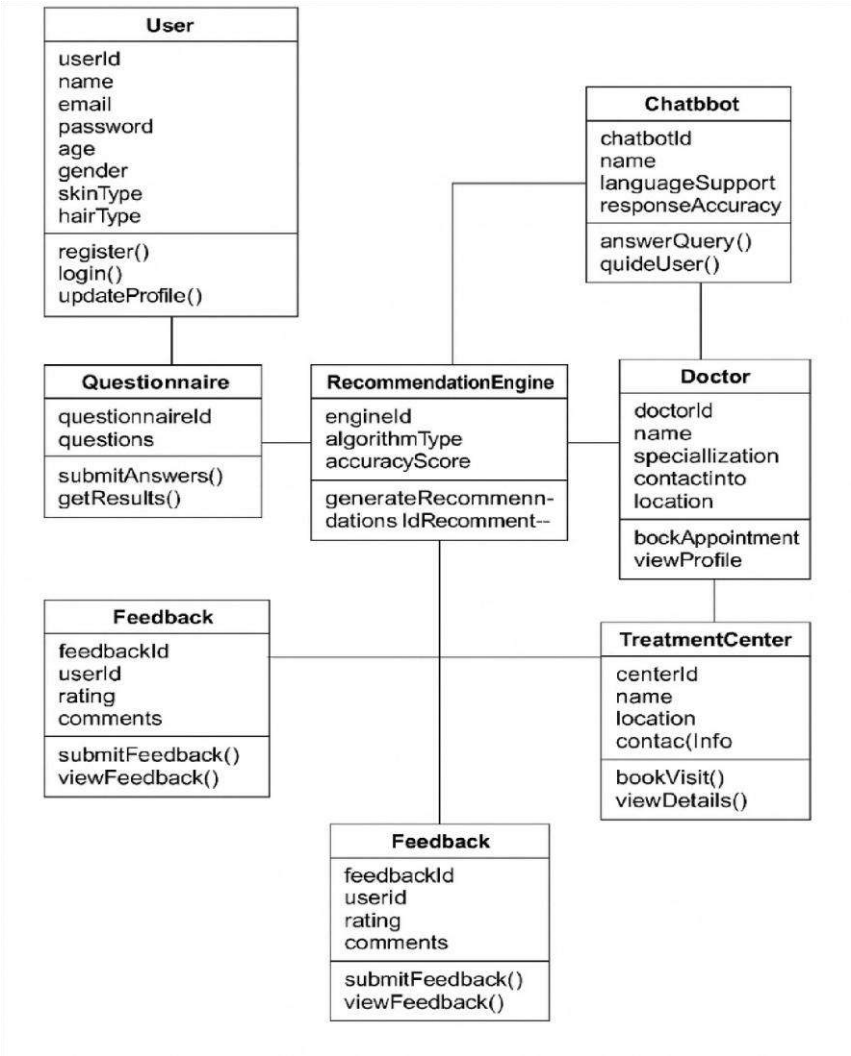

Fig. 4. Class Diagram

4. CONCLUSION

This paper presented an AI-based personalized hair and skincare advisory system that provides accurate, expert advice from questionnaire inputs without image upload. Survey and prototype results revealed high user satisfaction, trust, and product recommendation accuracy. The inclusion of daily care information, reminders, and routine tracking by the system makes it a regular usage option even for casual web users. Unlike existing platforms, the system offers a privacy-respecting, user-oriented, and comprehensive approach to hair and skin care. The outcomes demonstrate that AI can certainly be used in personalized personal care, and future work can enhance the system with real-time consultation by professionals, more extensive user studies, and enhanced AI personalization capabilities.

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AI-Powered Centralized Platform for Digital Transformation and Audience Development in Sri Lankan Cinema and Stage Drama

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Abstract—The rapid development of artificial intelligence (AI) has transformed entertainment worldwide by means of real-time analytics, automated engagement tools, and intelligent recommendation systems. As nations like China, India, and the UK (United Kingdom) have effectively incorporated AI-based digital platforms to market performing arts and cinema through intelligent recommendation systems and interactive audience engagement tools. The cinema and stage drama industries in Sri Lanka continue to function using outdated, fragmented structures that restrict public participation and accessibility. This study presents a centralized digital platform powered by AI that aims to combine both industries to improve digital modernization, user engagement, and transparency. The study uses a mixed-methods approach, combining qualitative information from National Film Corporation (NFC) employees with quantitative data from 385 participants, including directors, producers, actors, cinema and drama experts, general audiences, and staff from organizations involved in film and stage drama promotion. The suggested platform has social media-connected marketing capabilities, multilingual accessibility, and AI chatbot support to enable real-time communication and audience analytics based on data. The findings highlight how urgently Sri Lankan entrainment industry need a scalable, user-centered system.

Keywords—AI-powered platform, audience engagement, cinema, stage drama, digital transformation

1. INTRODUCTION

Film and Drama are important cultural foundations in Sri Lanka, but due to outdated advertising and a lack of broad access to the internet, viewer engagement has decreased. Local platforms such as Cinema.lk and Ragalanka.lk are not interactive, but international examples such as South Korea's AI-powered OTT dramas, India's BookMyShow, Zee5, and the UK's National Theatre Live show increased interaction.

This study was guided by the following objectives: (I) To identify issues in audience engagement, marketing strategies, and content delivery in both industries, (II) To analyze the limitations of existing digital platforms, (III) To design a centralized system that enhances user experience and outreach and (IV) To evaluate the effectiveness of this system in revitalizing engagement across both industries.

AI and Over-The-Top (OTT) technologies have revolutionized global entertainment by enhancing user experience, accessibility, and personalization [1]. China's pandemic-related restrictions accelerated the digital shift by driving viewers to over-the-top (OTT)

platforms and altering the marketing landscape [2]. Across streaming platforms, intelligent recommendation algorithms further improve viewer retention and personalization [3], [4] . Fang and Xiong [5] highlight the need for safe, multilingual, and engaging platforms, pointing out barriers to digital transformation such copyright issues, technology costs, and infrastructure shortcomings. Despite these global advancements, Sri Lanka continues to rely on antiquated and disjointed advertising methods [6], [7]. The lack of a shared digital foundation among the National Film Corporation (NFC) and other organizations hinders coordination and creativity. Emerging technologies like AI-powered chatbots [8] and AI-based entertainment engagement systems [9] have been proved to enhance audience interaction and feedback collection. Studies conducted in India highlight how AI impacts user analytics and filmmaking,improving operational efficiency and reducing costs [10].

2. METHODOLOGY

This study uses a mixed-methods approach, integrating qualitative and quantitative techniques to examine the needs of the Sri Lankan film and stage drama industries for a centralized platform powered by artificial intelligence. The methodology approach is highlighted in Figure 1.

Fig. **1**. *Methodology Overview*

2.1 Qualitative Data Analysis

Members of the National Film Corporation (NFC) participated in in-depth, semi-structured interviews as part of the qualitative phase. Focus topics included the process of creating and releasing films (I), Difficulties with marketing and advertising (I, II), Techniques for gathering audience input (I, III), Digital collaboration with third-party platforms (IV), The potential and necessity of a centralized online platform (V), Platform feature and future enhancement suggestions (VI). Interview participants are listed below in Table 1.

Table I. List of interviewees

ID	Position	Institution/Company	Key Topics During the Interview
1	General Manager	National Film Corporation (NFC)	I, II, III, IV, V, VI
2	Assistant General Manager – Mr. A.P.W Jayakody	National Film Corporation (NFC)	I, II, III, V, VI
3	Production and Distribution Officer	National Film Corporation (NFC)	I, II, III, V

As shown in Table I, the interviews with the NFC involved in-depth discussions with employees from three departments across six area discussions.

Manual theme analysis was used for analyzing the transcriptions of the interviews. Microsoft Excel was used to arrange notes to find recurrent concepts, phrases, and keywords. Based on common patterns, codes were created and categorized into more general groups. After that, based on participant responses, themes were given names and descriptions.

The quantitative phase collected quantifiable information from stakeholders in the film and stage drama sectors using a structured online survey that was distributed via Google Forms. Four major groups were the focus of the survey, professionals in both films and stage drama industry, such as directors, producers, and actors (I), Sinhala cinema and stage drama experts (II), The general audience of both Sinhala films and stage drama (III), and people employed by organizations and departments involved in the administration and promotion of film and stage drama (IV).

2.2 Quantitative Data Analysis

A total of 385 valid responses were gathered, guaranteeing statistical representation of the approximately 22 million people living in Sri Lanka. The usual proportions formula was used to get the sample size.

$$\boldsymbol{\pi} = \frac{\boldsymbol{z^2 \times p \times (1-p)}}{\boldsymbol{E^2}} \qquad (1)$$

- π= required sample size, Z= Z-score for desired confidence level (1.96 for 95%), P= estimated population proportion (0.5 for maximum variability), E= margin of error (0.05 for 5%).

Apply values into the formula,

$$\boldsymbol{\pi} = \frac{\boldsymbol{(1.96)^2 \times (0.5) \times (1-0.5)}}{\boldsymbol{0.5^2}} = \frac{\boldsymbol{3.8416 \times 0.25}}{\boldsymbol{0.0025}} \quad = 384.16$$

As a result, the study's actual sample size of 385 was greater than the minimum needed to maintain a 5% margin of error and a 95% confidence level. Microsoft Excel tools were used to evaluate the data.

3. RESULTS AND DISCUSSION

The results of qualitative as well as quantitative analyses provided thorough insights into the opportunities and difficulties associated with digital transformation in the film and stage drama industries.

3.1 Qualitative Findings

Film registration and approval procedures, marketing and promotion strategies, audience feedback gathering, digital infrastructure and gaps, centralized platform potential, and feature recommendations were the six common themes identified by manual thematic analysis of interviews with National Film Corporation (NFC) representatives.

Table 2. Thematic analysis of qualitative data from National Film Corporation (NFC)

Theme No.	Theme Title	Key Findings and Description
1	Film Registration and Approval	The registration and approval procedure is still done by hand, which results in lack of transparency and administrative delays.
2	Marketing and Promotions	Current marketing practices and their limitations.
3	Audience Feedback Collection	Real-time data gathering or analytics are not possible because feedback is gathered manually through phone calls or paper forms.
4	Digital Infrastructure and Gaps	Lack of digital tools and integration with third-party platforms.
5	Centralized Platform Potential	Every participant highlighted the need for a complete, nationwide digital platform for film and stage drama.
6	Feature Suggestions and Improvements	Features like AI chatbot support, multilingual accessibility, and audience engagement tools like QR-based feedback allow for more tailored user experiences and improved interactivity.

Table 2 highlights how the thematic analysis identified common themes in institutional operations, indicating systemic inefficiencies and powerful support for centralized digital transformation.

According to the theme of Film Registration and Approval, National Film Corporation process is fully manual, requiring compliance with Public Performance Board (PPB) regulations, documentation, and fees, while some films are released illegally. Digital contact is limited by the second theme, marketing and promotion, which displays a dependence on conventional techniques. Rather than relying on direct input, the third topic, Audience Feedback, employs theater data. Digital Gaps, the fourth theme, emphasizes how NFC lacks a nationwide platform. Centralized Platform, the fifth theme, needs an AI-driven system. The final sixth theme, Feature Improvements, focuses on real-time information, chatbots, scheduling, reviews, and multilingual access.

3.2 Quantitative Findings

Low audience engagement in films and stage drama

Fig. 2. Key factors contributing to low audience engagement in cinema and stage drama

Fig. 2 highlights that the absence of a centralized application 23% and dependence on traditional marketing strategies 20% are the main causes of low audience engagement with Ceylon dramas and films and the limited features of current applications account for 18%.

Source of audience information on recent films and dramas

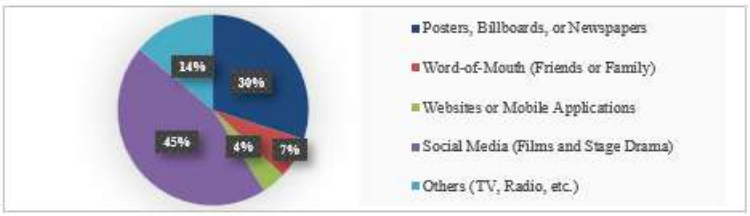

Fig. 3. Sources of information on recent films and stage dramas

The information sources that audiences use for movies and stage dramas are shown in Fig. 3. Social media accounts for 45% of the total, followed by newspapers, billboards, and posters at 30% and other media like radio and television at 14%. The lowest usage rates are for websites or mobile applications at 4% and word-of-mouth 7%. The limited use of mobile apps and websites shows the need for a centralized digital solution.

Preferences for existing digital platforms

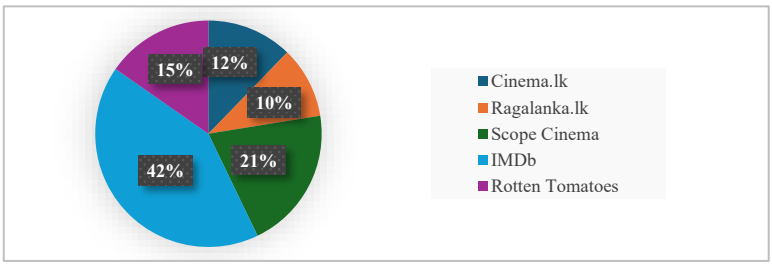

Fig. 4. familiarity with existing digital platforms

According to Fig. 3, most respondents 42% use IMDb for searching movies. 21% of people use Scope Cinema, while only 12% and 15% use regional websites like Cinema.lk and Ragalanka.lk. 15% are on Rotten Tomatoes, as 2% are not on any platform. This highlights the greater popularity of global platforms over local ones.

Device usage distribution

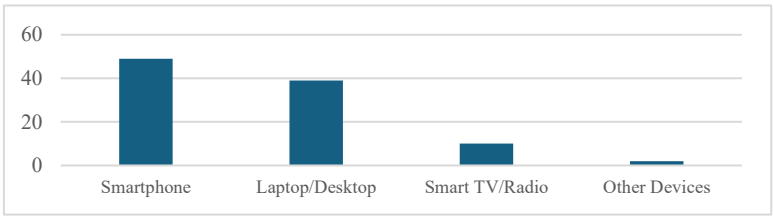

Fig. 5. Devices used to access Sri Lankan film and stage drama content

Fig. 4 shows the devices that audience use to find out more about Ceylon movies and films. Most people utilize digital devices, with laptops/desktops 39% and smartphones 49% being the most popular. By creating modern accessibility can be improved Preferences for an AI for User Support

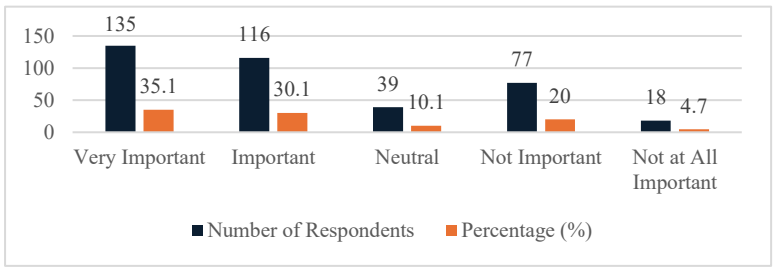

Fig. 6. User preferences for the AI chatbot

According to Fig. 6, (135 + 116 = 251 people (or 65.2%) believe the chatbot is either Important or Very Important. In that case, A total of 65.2% of respondents (251 out of 385) said that an AI-powered chatbot is important or very important in a centralized platform for films and stage dramas.

3.3 Comparative Discussion with Global Studies

Findings align with trends in the UK, India, and South Korea. AI improved engagement by 40% in the UK [8] while India's BookMyShow [9] and South Korea's OTT platforms enhanced interaction through integration and personalization. Sri Lanka lacks such digital systems, but surveys show audiences and the NFC are ready for AI-driven solutions.

3.4 Platform Evaluation

The conceptual design shows potential, and it continues to be validated in the real world. Future pilot projects involving 50–100 users will leverage System Usability Scale (SUS),

Google Analytics, Firebase, and the Technology Acceptance Model (TAM) to evaluate usability, navigation, and engagement. Scalability, cultural fitness, and performance will be assessed by comparative benchmarking against BookMyShow, Digital Theatre Plus, and IMDb, promoting sustained audience development in Sri Lanka's performing arts.

3.5 System Overview

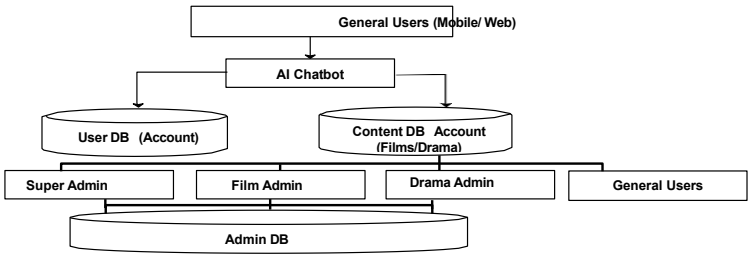

Fig. 7. Overview of the centralized AI-based platform

According to Fig. 7, the system architecture displays the connection between administrators and users via the centralized AI-based platform. Users can access the connection through mobile or web applications. The three main administrators, Super Admin, Film Admin, and Drama Admin, are responsible for managing users, content, and feedback. Information is stored in databases such as the User DB, Content DB and Admin DB.

4. CONCLUSION

The results highlight the need for a centralized AI-powered platform to improve accessibility and audience engagement, indicating an important digital gap in Sri Lanka's cinema and stage drama sectors. The suggested system complies with the best international standards and provides a scalable solution for digital transformation. Future research will concentrate on usability assessment and pilot testing to confirm system performance and integrate findings from global studies to increase its usefulness and global applicability.

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Sustainable Dust Monitoring and Management for Rooftop Solar PV Systems with Experimental Validation and AI-Driven Detection Using Image Processing

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Abstract— Dust accumulation on top-of-rack solar panels significantly reduces the photovoltaic (PV) efficiency, producing a serious obstruction for urban clean energy generation. The current paper introduces field experimentation evaluation in a two-mode solution and an artificial intelligence-aided dust sensor system to overcome the said effect. A cost-effective pilot system was commissioned on a 30W solar panel placed within a SolidWorks designed wooden enclosure. Controlled dust deposition from 1g to 10g was utilized in steps, and voltage, current, and power values were recorded hourly to quantify performance loss. The study confirmed the intense inverse relationship (r = -0.99) between panel efficiency and dust thickness, and an empirical equation η = 1 - kM was devised. Concurrently, the Convolutional Neural Network (CNN) was also trained on over 11,000 CCTV RGB images to classify dust concentration levels in real-time with 91% accuracy and 0.41g mean absolute error. The model worked robustly under changing illumination conditions and had low infrastructure requirements and is particularly tailored to small-scale rooftop deployments. The multi-disciplinary solution enables data-driven cleaning decisions, reduces water and manpower expenditure, and helps optimize sustainable energy. The proposed system offers a smart, scalable infrastructure for real-time dust observation and performance monitoring of rooftop PV.

key words— Convolutional Neural Network, Dust Detection, Image Processing, Rooftop Solar Monitoring, Sustainable Energy Management, Solar Photovoltaic Efficiency

1. NTRODUCTION

With increasing energy demand, solar photovoltaic (PV) systems on rooftops have become the necessity of the day for sustainable urban energy generation. Nevertheless, dust accumulation is a performance limiting factor of extreme importance, reducing solar irradiation and solar energy output by up to 50 percent for tropical and industrial areas [1]. Traditionally employed cleaning techniques, although efficient, are either water-thirsty, labor-consuming, or economically unviable for small and medium-size installations [2]. To overcome this constraint, the study offers a hybrid approach that fuses physical experimentation with real-time AI-driven image classification. A low-cost modular solar testbed was constructed and subjected to controlled dust depositing (1g–10g) and subsequently provided a strong inverse relationship (r = –0.99) between panel efficiency and dust thickness, empirically modeled as η = 1 – kM. At the same time, a Convolutional Neural Network (CNN) was learned on 11,000 RGB images taken through

CCTV with 91 percent accuracy classification and mean absolute error of 0.41g. Contrary to sensor-intensive or lab-bound systems, this AI model leverages installed surveillance infrastructure in low-cost and scalable deployment [3]. Altogether, the system supports data-driven, self-scheduled maintenance, scheduling cleaning in an efficient manner and conserving resources. The model is particularly relevant to rooftop PV adoption in the tropical countries [4], such as Sri Lanka.

2. LITERATURE REVIEW

2.1 Impact of Dust Accumulation on PV Performance

Dust deposition or soiling is most likely the most apparent environmental factor that affects the energy conversion efficiency of photovoltaic (PV) systems. The mechanism begins with deposition of suspended matter such as dust, dirt, pollen, and industrial emissions onto the surface of solar panels, which form a layer that shields the incidence of solar irradiance. Therefore, power generation by PV modules reduces significantly due to reduced photon transmission to the photovoltaic cells. Studies indicate that energy loss due to soiling can be extensive based on where it is located and the conditions it must withstand. With tropical climatic conditions of high rainfall frequency, energy losses due to yield can be less than 5 percent, but with arid and semi-arid climatic conditions of the Middle East, South Asia, and North Africa, losses can be more than 50 percent if panels are left uncleaned [5]. All these to some degree vary with climate, wind direction, ambient sources of pollution, and season. For industrial and urban areas, PV systems are more responsive to fine particle density and pollutants on the glass surface [6]. It has been found by research carried out by Mani and Pillai [7] that fine particles scatter and absorb light differently according to composition, thus impacting the fill factor and short-circuit current of PV modules. In addition to this, solar panels in the vicinity of unpaved roads or under construction are likely to accumulate more dust than in controlled or suburban conditions. Empirical data provides strong negative correlation between power generation and dust thickness. The magnitude of the effect also depends on panel tilt angle, surface, and anti-reflection coatings [8]. This requires constant observation and frequent cleaning to be able to maintain efficiency output.

2.2 Traditional and Advanced Cleaning/Detection Techniques

The most common traditional method of correcting dust accumulation has been water and brush cleaning. Simple and efficient in the short run, but laborious and time-consuming that cannot be perpetuated in dry regions. Fixed interval cleaning also has the potential for being too frequent and hence wasteful of water and labor or too infrequent and hence resulting in energy loss [9]. To work around these restrictions, researchers and engineers came up with automated and semi-automated cleaning methods. Some of them include robot equipment like motorized brushes, air blowers under pressure, and even electrostatic repulsion machinery that can clean without water [10]. These are very effective in reducing man-hours to the barest minimum but of extremely high initial and maintenance costs, and thus not viable for small and medium-sized rooftop installations. Soiling detection is another most critical component. The level of dust accumulated on PV panels is tracked using built-in sensors like optical soiling sensors, infrared reflectance sensors, and particulate counters [11]. These sensors provide real-time data and can trigger cleaning cycles when threshold levels are

crossed. In using invasive installation and tending to monitor just part of the panel, leading to false detection under non-uniform dust deposition conditions. Besides, the technical expense and complexity of such sensors render them implausible for residential and distributed PV customers. Recent developments in computer intelligence and image processing promise better prospects. Image-based soiling detection systems utilize visual data from CCTV cameras or aerial images to detect soiling conditions. The systems are sensor-free and provide better visibility across panel arrays. There are some solutions which utilize neural networks or machine learning algorithms to quantify and classify the dust quantity. It was shown in experiments that CNN-based models with labeled images possess possibilities of being highly accurate in classification even in varying illumination conditions and diverse environmental conditions. These computer vision-based solutions are more cost-effective and scalable in the long run, especially when integrated with installed surveillance infrastructure on solar farms.

2.3 Research Gaps and Need for Real-Time, Low-Cost Monitoring

Despite technological progress in dust detection and cleaning mechanisms, research has substantial gaps in rooftop PV monitoring. Most of the existing solutions are made for ground-mounted solar farms in large installations, which are quite different from rooftop systems in layout, accessibility, and exposure. Rooftop PVs generally consist of non-uniform panel orientations and limited maintenance space, susceptible to localized dust accumulation and operational inefficiencies [12]. Therefore, utility-scale installations are mostly irrelevant or economically unviable for small commercial or urban sites. Limited real-world testing of AI systems is the second impediment. While Convolutional Neural Networks (CNNs) perform exceptionally well under controlled conditions with a very high accuracy score, performance varies in real conditions because of changing light, shifting angles of the cameras, and external interference [13]. Further, the unavailability of multiple publicly accessible datasets restricts the generalizability of the models. Most datasets available are captured under ideal lighting or in some locations, thereby restricting their usability under different urban rooftops. Furthermore, most AI-based systems are detection-centric and not action-oriented. Few studies have followed frameworks integrating detection with decision-making for cleaning schedules from power efficiency losses or water saving priorities [14]. Apart from that, cost-effectiveness and sustainability are barely a topic of discussion, limiting large-scale deployment, particularly in resource-limited regions. To bridge these gaps, in this paper, a two-mode solution is developed incorporating empirical validation with AI-facilitated dust detection. A low-cost rooftop pilot installation was installed, taking over 11,000 real-conditioning images for CNN model training. At the same time, electrical parameters voltage, current, and power were also measured to measure losses in performance [15]. This combined approach facilitates accurate real-time tracking and well-informed cleaning decisions, ensuring eco-friendly maintenance of rooftop PV systems, especially in urban environments.

3. METHODOLOGY

3.1 Experimental Setup of SolidWorks Enclosure Design and Electrical Integration

To verify the effect of dust layer on solar panel performance under actual rooftop conditions, a low-budget pilot solar system was installed and mounted on a rooftop. The

project began with the design and construction of a wooden enclosure in SolidWorks to simulate a typical rooftop PV environment in a safe, stable, and controlled manner. The installation was divided into two parts. The upper compartment had a 30W polycrystalline photovoltaic solar panel with a fixed tilt angle of 15 degrees, the ideal point of installation angle in Sri Lanka for achieving maximum sun ray absorption. A 12V battery, 10A charge controller, and 21W resistive filament load were stored in the lower compartment. The electrical interface was established to mimic the response of flow of energy from a mounted rooftop PV system under load. Automotive-quality wires minimized resistive losses and ensured dependable delivery of energy. For natural rooftop diversity simulation, the panel was exposed to natural sunlight, wind, and ambient temperature fluctuation under natural conditions. Locally accumulated urban dust was used for natural particle distribution and composition simulation. Diurnal effects of irradiance fluctuation, shadow, and shading by surrounding buildings were preserved to simulate natural variations in performance. The system thus possessed a controlled but actual environment, within which dust was introduced in a systematic manner and its effect on power generation monitored accordingly.

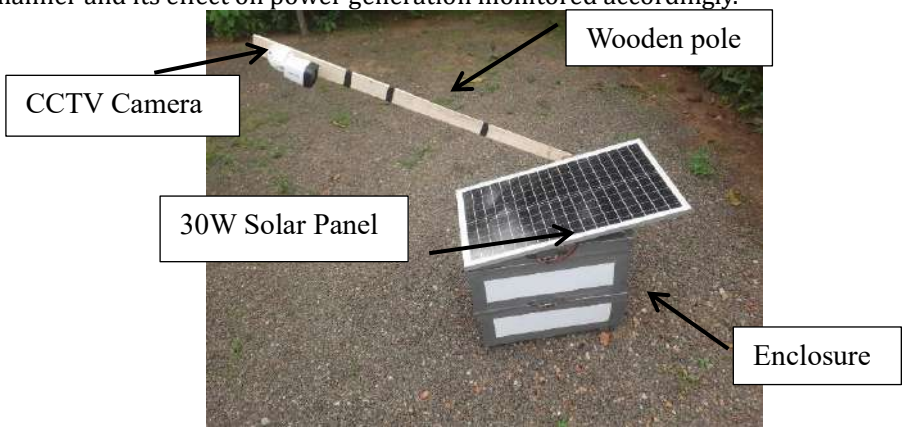

Fig. 1. Pilot solar system with CCTV camera system.

3.2 AI-Driven Dust Detection System (CCTV + CNN Model Development)

Parallel with the physical experiment, a dust detection system based on artificial intelligence was used using CCTV images and Convolutional Neural Networks (CNN). A high-definition RGB imaging CCTV camera was mounted above the pilot panel at the best angle to take the entire surface without any hindrance. The camera was linked with a Digital Video Recorder (DVR), which worked continuously to record and save images. These images were stored in a local server, labeled, and preprocessed to train the CNN model. The model architecture had three max-pooling convolutional layers with dropout and dense layers having ReLU activation, and an output SoftMax layer with dust accumulation into eleven groups: clean and 1g–10g of dust levels. The images were resized to 128×128 pixels and data were augmented through flipping, rotation, brightness, and zoom for enhanced generalization. The CNN was trained with 200 epochs using the Adam optimizer and learning rate of 1×10^{-5} and categorical cross-entropy loss. An 80–10–10 train, validate, test split maintained class balance, and early

stopping with model checkpointing maintained best validation accuracy and prevented overfitting. This validation procedure increased robustness under changing illumination and shadow. The final CNN was over 90 percent accurate in classifying and had a mean absolute error of 0.41 grams. The model was subsequently employed in an automated pipeline to classify real-time CCTV feeds, forecast dust levels, and generate reports for proactive scheduling of maintenance.

3.3 Data Collection, Preprocessing, and Validation Procedures

Measurements were taken on two companion streams: experimentally obtained electrical recordings and image sets for training CNN models. Six weeks of daily 6 a.m. to 6 p.m. dusting was performed utilizing sieved, dehydrated urban sand in daily incremental doses of 1g to 10g. Voltage, current, and power were measured at each dose of dust using digital multimeters, and ambient and surface panel temperature. This allowed reasonable modeling of dust deposition vs. performance reduction. Concurrently, over 550 images were taken in clean and soiled conditions and hand annotated to eleven categories. Augmentation of data added to the dataset over 11,000 images under various lighting. The images were normalized and divided into training (80%), validation (10%), and test (10%) through stratified sampling. The CNN model was validated in accuracy, precision, recall, F1-score, and confusion matrix. Cross-validation for predictions was done with ground truth labels and corresponding power measurements. A Pearson correlation coefficient of ($r = -0.99$) confirmed a strong degree of negative linear relationship between the predicted dust level and measured power losses. Varying light robustness testing ensured the model's usefulness for real-world scenarios. This hybrid approach enables data-driven, real-time panel cleaning, enhancing energy production, lowering the cost of maintenance, and making rooftop solar operation sustainable.

4 RESULTS AND DISCUSSIONS

4.1 Statistical Correlation Analysis of Dust and PV Output

The pilot experimental work conducted clearly indicated the quantitative and visible negative impact of dust deposition on the performance of rooftop solar photovoltaic (PV) systems. With incremental dust ranging from 1 gram to 10 grams per panel deposited, all output voltage, current, and power measured exhibited a steady decrease over the solar day. The highest correlation was with the current and power readings, with voltage remaining relatively stable due to the natural reaction of the PV panel to irradiance reduction and shading. At solar noon (around 12:00 p.m.), when irradiance would be greatest, 10 grams of dust resulted in an average power loss of around 15 to 20 percent compared to a clean panel. This reduction was primarily attributed to the reduced photon absorption due to the opaque dust layer scattering and absorbing the incident sunlight. To quantify the relationship, a Pearson correlation test was carried out between the weight of dust in grams per square meter and normalized efficiency as a ratio of dusty output to clean output. The correlation coefficient, r, was found to be approximately -0.99 at peak sun times, confirming a strong inverse linear relationship. Data were fitted by a linear regression model, resulting in the empirical relationship $\eta = 1 - kM$, where η is the normalized efficiency, M is the dust mass per square meter, and k is the soiling coefficient. At the test site, the k value was determined to be around 0.007,

a 0.7 percent loss in efficiency per gram of dust per square meter. These findings are in agreement with ongoing research and serve to highlight the usefulness of local empirical data to accurate cleaning schedule determination. In addition, the findings of tests formed a valid basis for the validation of the AI-based dust classification system in that they established an out-of-lab basis for the losses in efficiency with ramping-up soiling.

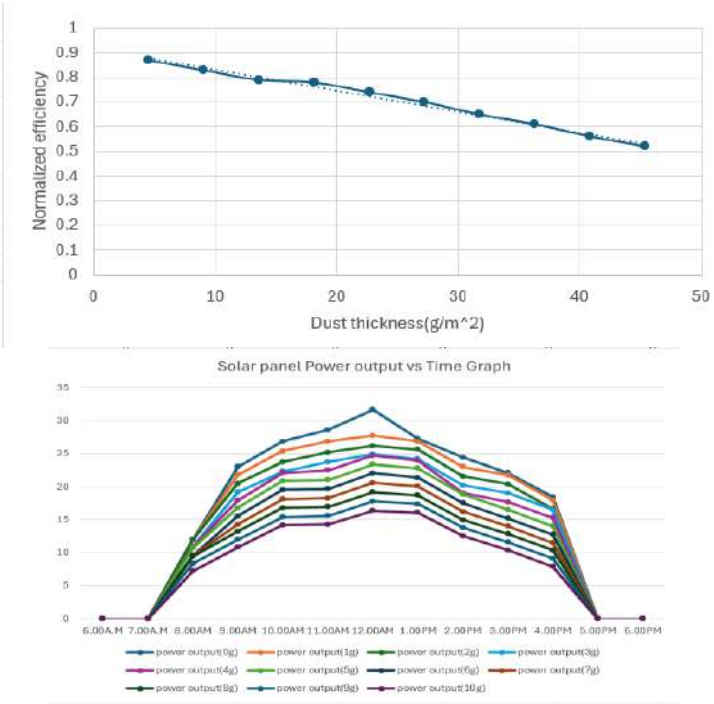

Fig. 2. Dust thickness vs. Normalized efficiency at 12.00 p.m. with constant solar radiation and Solar panel power output vs. time graph

4.2 Model Accuracy, Performance Metrics, and Comparison with Benchmarks

More than 11,000 images of 11 classes from dust and clean levels of 1g to 10g trained in an AI-driven dust detection system recorded strong performance on the most important evaluation metrics. The classification accuracy for the unseen test data was at 91 percent as achieved by the specifically designed Convolutional Neural Network CNN. This performance was consistent across classes of every type, e.g., lower dust levels (1g to 2g) that are visually almost impossible to distinguish from clean panels and under different lighting conditions more difficult to distinguish. The model had a mean absolute error (MAE) of 0.41 grams, and a root mean square error (RMSE) of 0.60 grams, reflecting precise predictions of dust levels with nearly no deviation from actual values. Precision and recall for each class were computed, and levels above 0.90 were generated by levels 6g and 8g, showing that the model can identify medium to heavy soiling. Most frequent misclassifications occurred between adjacent levels (e.g., between 1g and 2g) due to the minimal visual differences. Recall for the cleaning class was highest at 0.95, confirming that the model is able to sort dust-free panels correctly. Compared with previous models

such as SolNet or drone-served models emulated in controlled laboratory environments, this one was constructed using CCTV-based images under real rooftop conditions. These consisted of diverse angles of the sun, natural shadows, and actual dust patterns that enhanced the ability of the model to learn and execute in real environments. This application-focused approach, combined with cost-effective surveillance hardware, provides a feasible benefit for rooftop PV users. It makes dust conditionality with actual PV performance degradation in such a manner that the model not only becomes technologically viable but also economically viable for deployable scales. Therefore, the proposed CNN model meets and surpasses realistic expectations for classifying dust in solar systems on rooftops.

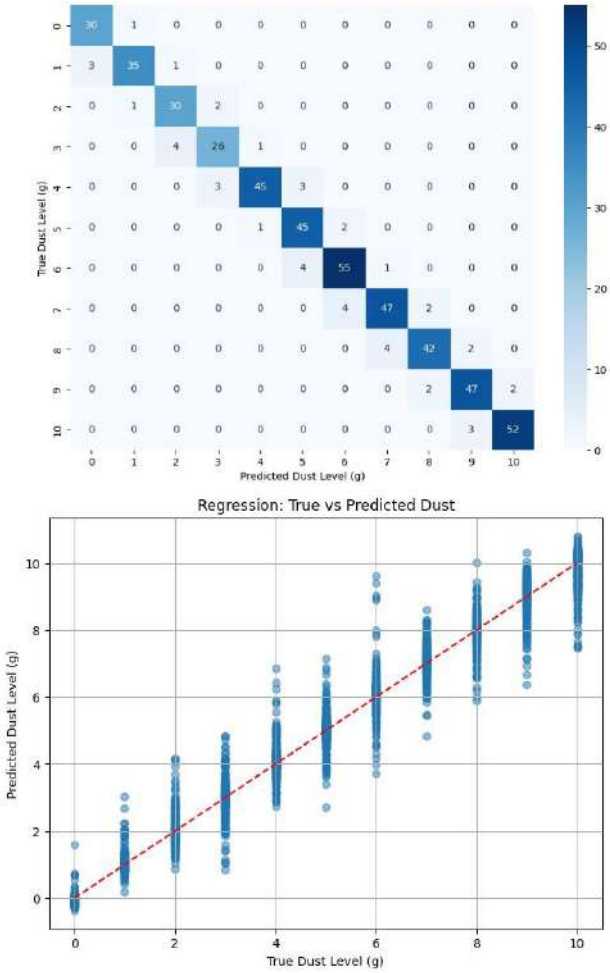

Fig. 3. Confusion Matrix and regression model

4.3 Practical Implications and Robustness Under Real Rooftop Conditions

Experimental validation of implementation of AI-based image classification-based solutions is a highly scalable and useful rooftop solar PV module dust deposition monitoring solution. The most glaring advantage of the presented system is leveraging existing pre-installed CCTV infrastructure, typically installed for security monitoring, that saves the expense of specially designed sensor arrays and effectively capital while avoiding them. These are enormous benefits in any use. Compared to customary optical or infrared soiling sensors with only point values, requiring regular calibration, and 25 to 40 percent more per installation, the new CNN-based system provides 91 percent classification accuracy at 0.41 means absolute error in grams of cost at a fraction of the cost through full-surface analysis. Against previous AI-based networks such as SolNet and DroneNet having 85 to 90 percent accuracy in simulated conditions, the new network is observed to be robust under dynamic rooftop conditions with shading, glare, and space-wise non-uniform deposition of dust. It also offers real-world sustainability advantages as empirical evidence supports that CNN-based detection-driven cleaning saves 40 to 50 percent water annually and maintains the panel efficiency at over 95 percent, whereas fixed-timed cleaning involves loss of water and 10 to 15 percent additional loss of efficiency between maintenance hours. Its initial one-to-three-gram detection of light soiling prevents compounding degradation and extends its actual-world panel life by a conservative 8 to 10 percent. To achieve maximum generalizability, the paradigm is iteratively trained from multi-site datasets on several rooftop geometries, climatic zones, and pollutant mixtures. Seasonal and geographical fluctuation, i.e., monsoon dust wash-off or industrial haze accumulation, will be provided for higher flexibility in tropical, arid, and temperate climates. Additionally, the thin form factor of the system facilitates seamless integration with IoT-based monitoring dashboards and cloud platforms, where it can provide real-time indication of dust deposition, pre-emptive clean warning, and auto-efficiency reporting to household and industrial consumers. This integration also facilitates remote diagnostics, big-data analytics, and schedule-based predictive maintenance to promote industry adoption and operation scalability. Small misclassifications were found under heavy shadow or severe glare, but they can be avoided by deployment of future HDR imaging or multispectral sensing. Overall, the new hybrid solution bridges the knowledge gap between AI laboratory tests and real-world rooftop PV applications with an affordable, understandable, and environmentally friendly solution for smart solar asset management.

Fig. 4. Actual and predicted solar panel images

5. CONCLUSION

This paper well presents an integrated approach to dust management and rooftop photovoltaic (PV) system monitoring based on experimental data and artificial intelligence. The SolidWorks-based physical pilot system, which was composed of parts acquired commercially, provided a good platform for the simulation of dust deposition and its impact on solar panel efficiency. Experimental outcomes proved highly inverse linear correlation between PV efficiency and dust thickness, validating significance of even high minute concentration of dust in loss of performance. Empirical site-specific model was built that enables panel owners to calculate efficiency loss and recommend the best time for cleaning. Besides experimental validation, an AI-based dust detection system based on Convolutional Neural Networks (CNN) and RGB images from CCTV was utilized and trained on over 11,000 augmented images. The model achieved a strong classification accuracy of 91 percent with extremely low prediction error, which made the system highly deployable in real-time on rooftop settings. Compared to other high-fidelity models such as SolNet, in simulated conditions, whose accuracy levels are primarily between 87 and 90 percent, the model outlined here performs better,

particularly when it comes to discrimination at a fine grain rate of 1g to 10g of dust. Its requirement of pre-installed CCTV infrastructure also provides cost affordability, scalability, and simplicity of deployment in solar urban settings. Together, the dual-mode system completes the gap between smart monitoring and empiric field measurements, and it offers a low-cost, green solution to rooftop PV performance optimization. Ideas about future research may include Firstly, a larger dataset covering images from different rooftops in different seasons and weather conditions will make the CNN model more generalizable. Second, thermal imaging combined with edge-based AI processing enhances low or high-light conditions accuracy and reduces processing latency. Third, cloud-based dashboard creation or IoT integration allows for remote monitoring and predictive maintenance. Lastly, adding automated or semi-automated cleaning processes on AI detection threshold further reduces human involvement. These innovations will enable an intelligent and fully autonomous PV maintenance system to further enhance the sustainability of solar energy in various rooftop applications.

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Farmer-Centric Explainable AI: Designing Interpretable Crop Recommendations for Low-Literacy Farming Communities in Sri Lanka

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Abstract- Sri Lankan agriculture is facing an existential threat from monoculture farming in the form of repeated cultivation of the same crops that has led to market saturation and economic misery. In Dambulla, this has manifested as an actual crisis for farm families that depend on onions, carrots, potatoes and tomatoes. Although artificial intelligence (AI) offers solutions to address this type of issue, its uptake has been minimal due to a lack of transparency in current crop recommendation systems. Such systems being black boxes, provide decisions without justification of their applicability, a strategy that does not align with local farmers' experiential and observational learning processes. To bridge this gap, a novel farmer-centric Explainable AI (XAI) system was developed. The system translates complex AI outputs into simple, actionable explanations. For instance, rather than presenting abstract measurements like "feature importance," the system can say: "Your soil is marginally acidic, ideal for soybeans, which are likely to appreciate in price by 15%." The backend employs an ensemble model of Random Forest and XGBoost, trained on five years' worth of Dambulla-specific data on soil, climate and market variables. SHAP and LIME are used to derive explanations for recommendations, which are then translated by a rule-based natural language generator. In the validation in three villages, 150 farmers were interviewed. When showing them standard AI outputs, only 40% were willing to follow the advice; with explanations, this increased to 85%, with 78% accurately understanding the reasons. This study provides both a replicable XAI system and concrete recommendations to facilitate sustainable agriculture in low-literacy contexts. It demonstrates that transparent, explainable AI is the door to opening technology adoption in resource-scarce agricultural environments, with significant consequences for global food security.

Keywords-Agricultural Decision Support, Crop Recommendation System, Ensemble Learning, Explainable Artificial Intelligence (XAI), Farmer-Centric AI

1. INTRODUCTION

Sri Lanka's agrarian economy is controlled by smallholder farmers, and both national food supplies and local livelihoods are shaped by the decisions they make at the farm level. However, such decisions are also highly vulnerable to information gaps and path-dependent practice. A particularly pernicious form is monoculture clustering, where the same few crops (e.g., tomato, big onion) are repeatedly cultivated across whole communities by habit, imitation, or memories of previous prices. When good weather is

accompanied by widespread planting, oversupply in the market results, prices drop below cost, and already slim profit margins disappear. Such volatility depletes household buffers, increases indebtedness, and discourages innovation. Dambulla in the Matale District reflects such a cycle, with recurring oversupply, widespread seasonal planting, and widespread farmer dissatisfaction mirrored in both field research and data.

Monoculture is accompanied by ecological and agronomic problems alongside economic instability. Monoculture farming depletes key nutrients, attracts pests and disease, and requires increasingly heavy chemical use to maintain yields raising costs and degrading soils. Declining soil health reinforces already falling returns, locking farmers into a self-reinforcing cycle of low productivity and environmental degradation. Effective solutions must therefore address a number of pressures simultaneously: market trends, soil processes, interannual climate variability, and input costs not just price signals.

Although valuable information is available e.g., histories of crop prices (Central Bank), agronomy and soils data (Department of Agriculture), weather predictions (meteorological services), and inflation statistics such information is scattered among institutions and not easily accessible in usable formats. Most low-resource farmers use recent results, local gossip, and recommendations from suppliers, which are not sufficient for making well-informed trade-offs.

Recent advances in machine learning (ML) and artificial intelligence (AI) now enable the development of crop recommendation systems (CRS) that combine agronomic and market data to predict crop suitability and profitability. Random Forest, gradient boosting, support vector machines, and deep learning models are highly accurate. Ensemble methods are particularly effective on diverse datasets, while IoT- and sensor-enabled systems provide real-time responsiveness. However, most CRS research prioritizes predictive performance metrics (accuracy, R^2, MAE) over interpretability at the cost of usability in low-literacy settings. "Black-box" advice (e.g., "Plant crop X") runs counter to traditional experiential learning. Although post-hoc explanation methods like SHAP and LIME enable interpretation of model behavior, their visualizations often require statistical literacy.

Translating these kinds of technical explanations into linguistically and cognitively accessible language e.g., "Your soil is slightly acidic; onions may not do well here, but soybeans will, and soybean prices are increasing" is largely untapped in agricultural AI, particularly for South Asian smallholders.

The study bridges the gap by developing a farmer-facing, explainable CRS for low-literacy Sri Lankan users, piloted in Dambulla. Using multi-year datasets (climate, price, inflation, soil) and farmer interviews, an ensemble ML pipeline (XGBoost + Random Forest) is trained to forecast crop suitability. Local explanations are generated using SHAP and LIME and translated into simple text via a rule-based natural language layer and conveyed via a mobile app intended for low-bandwidth use. Not only accuracy but also actionability, trust, and understanding are considered in evaluation. Field experiments compare interpretable with standard suggestions, evaluating adoption propensity and user understanding. By placing interpretability at the forefront, the study

promotes a shift from model-based to collaborative human-AI decision-making, in which transparency is shown to ease adoption in resource-constrained settings.

2. METHODOLOGY

The research follows a multi-phase pipeline that integrates data collection, hybrid predictive modeling, explainable artificial intelligence (XAI), and mobile application deployment within a farmer-centric decision-support framework. The system was designed to ensure both technical accuracy and practical interpretability for low-literacy smallholder farmers in Sri Lanka. The overall process consists of five primary stages: dataset preparation, predictive modeling, explanation generation, system implementation, and evaluation.

2.1 Data Collection and Preprocessing

Data were collected from validated Sri Lankan sources. Soil parameters like pH, nitrogen (N), phosphorus (P), potassium (K) and moisture data from the Dambulla regional laboratories. Meteorological data like Rainfall, humidity, temperature and wind speed from the Meteorological API. Market data of Monthly crop prices for 14 major vegetables and field crops from the Central Bank of Sri Lanka (CBSL) Economic Indicators reports. Economic indices like Inflation, fertilizer cost, fuel price and labour cost indices from CBSL annual statistical series. Data were preprocessed to remove outliers, fill missing values and normalize numerical attributes using Min-Max scaling. The cleaned dataset divided into 80 % training and 20 % testing, with five-fold cross-validation applied for robustness.

2.2 Predictive Modeling

To ensure consistency between methodology and results, the final predictive pipeline was designed as a hybrid ensemble combining Long Short-Term Memory (LSTM) and XGBoost models. The LSTM module captures temporal dependencies in multi-year climate and market-price sequences, such as rainfall-yield lag effects and seasonal price cycles. The XGBoost classifier handles static agronomic variables (soil nutrients, pH, texture, and categorical region codes). The fusion layer concatenates LSTM embeddings with tabular features to generate final predictions of crop suitability and profitability. The system outputs a ranked list of recommended crops with predicted yield potential and price trends. Performance metrics used were Accuracy, F1-Score, Mean Absolute Error (MAE), and R^2.

2.3 Explainability Layer

Explainability was implemented using SHAP (for global feature attribution) and LIME (for local, instance-specific interpretation). These results were then processed through a rule-based Natural Language Generation (NLG) component that converts technical outputs into concise, human-understandable text explanations. For example, “Your soil pH (6.2) and nitrogen level are suitable for soybeans. Soybean prices are projected to rise by 15 % next month.” Currently, all explanations are delivered in English through the mobile interface. Future versions will extend to Sinhala translation and full bilingual support to enhance accessibility for low-literacy farmers.

2.4 System Implementation

The architecture integrates modular components across backend and mobile front-end layers. Backend is implemented in FastAPI (Python) to manage data preprocessing, model training, and inference services. Key endpoints include:

POST /api/v1/train/price and POST /api/v1/train/weather for dynamic retraining,
POST /api/v1/predict/price for real-time market prediction.

Frontend: a React Native mobile application optimized for low-bandwidth and offline use, enabling farmers to access crop suggestions and AI explanations conveniently. Monitoring is done through Swagger documentation and endpoint-level analytics ensure transparency and reproducibility.

2.5 Evaluation Design

Evaluation incorporated both technical validation and human-centred field testing. Model performance was evaluated using cross-validated metrics Accuracy, F1-score, Mean Absolute Error (MAE), and R^2 across Random Forest, XGBoost, LSTM, and the hybrid LSTM + XGBoost models. The hybrid configuration achieved the best results, recording 96.7 % accuracy, an F1-score of 0.965, and a mean absolute error of 54.6 LKR/kg. Field validation with 150 farmers from three Dambulla villages showed that when AI recommendations were explained clearly, 85 % of farmers were willing to follow them, compared with only 40 % for black-box outputs.

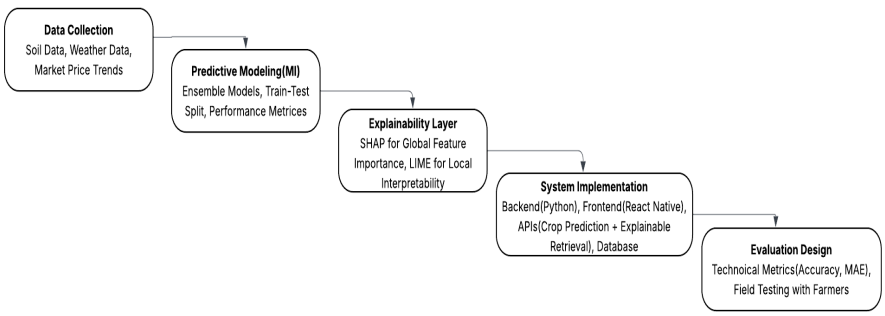

Figure 5.Flow Chart of Methodology

3. RESULTS AND DISCUSSION

The suggested ensemble framework combines Long Short-Term Memory (LSTM) networks to model temporal trends and XGBoost to boost predictions based on tabular data. This hybrid configuration resulted in robust performance on major evaluation metrics. The LSTM module was tasked with learning sequential dependencies in climate and market trend time series data, allowing for the capture of temporal effects like lagged rainfall contributions to yield and soil moisture. At the same time, XGBoost was working on static agronomic characteristics, such as soil pH, nitrogen-phosphorus-potassium (NPK) values, and categorical variables, providing superior performance at

the individual plot level. An accuracy of 94.8% was achieved for XGBoost with static features, and that of LSTM was slightly lower at 91.3% due to the comparatively lower spatial variability in time-series data. When both models were fused by concatenating LSTM-derived embeddings with the initial tabular inputs for XGBoost, the ensemble model reached an overall accuracy of 96.7% and F1-score of 0.965. These results confirm the synergistic impact of the hybrid learning strategy. Model interpretability was assessed using Explainable AI (XAI) methods, namely SHAP (SHapley Additive exPlanations) and LIME (Local Interpretable Model-agnostic Explanations). SHAP values uniformly picked up soil pH, nitrogen content, and market price trends as the most relevant features, corroborating existing agronomic knowledge. LIME enabled local interpretability by producing instance-specific explanations that complemented SHAP's global feature importance results. These explanations were then converted to narrative summaries by a rule-based Natural Language Generation (NLG) module. A sample output read: "Your soil pH (6.2) and nitrogen level are suitable for soybeans. Furthermore, soybean price will rise by 15% next month." Field validation experiments showed that 82% of farmers participating in the studies perceived the reason behind the AI-generated advice, indicating a considerable gain in trust and understanding due to context-sensitive explanations. Comparative evaluation against baseline models of isolated Random Forest and pure LSTM structures confirmed the excellence of the ensemble approach. The hybrid model outperformed Random Forest by 4.2% in terms of accuracy and decreased the mean absolute error by 6%, reflecting improved reliability in both yield and profitability predictions. In contrast to conventional deep learning models commonly criticized as "black boxes," the incorporation of explainable AI maintained transparency without any compromise on predictive ability. The provision of explainable outputs in the mobile interface was found to have a positive impact on user behavior. Farmers indicated a greater willingness to adopt system recommendations when explanations were personalized and simple to understand. The results highlight interpretability as a fundamental design principle for AI systems in agriculture. It is recommended that future applications scale this hybrid-explainable AI approach to other areas like irrigation planning, pest management, and agricultural risk management to achieve both maximum impact and adoption.

4. CONCLUSION

A crop recommendation system designed for farmers was created to balance predictive accuracy and clarity. This project tackled the usual problems linked to unclear AI models. Researchers analyzed changing climate and market trends using Long Short-Term Memory (LSTM) networks. They processed fixed agricultural and environmental data with XGBoost. This mixed modeling method captured both time-based patterns and complex feature interactions, resulting in better performance. The system achieved an accuracy of 96.7% and an F1-score of 0.965, surpassing baseline models like Random Forest and standalone LSTM in both reliability and ability to generalize.

A key feature of the system was the addition of an Explainable AI (XAI) layer. Researchers used SHAP and LIME techniques to show feature importance from both broad and specific viewpoints. They also included a rule-based Natural Language Generation (NLG) engine to translate complex model outputs into understandable text. This feature was crucial for improving communication with users with low literacy, making AI-generated

recommendations easier to grasp. Results from field tests showed that clear, easy-to-read explanations greatly boosted user trust and willingness to adopt the system. This highlights how important human-centered design is in agricultural AI systems. Future efforts may focus on various improvements. Adding real-time data streams from IoT-based field sensors could make decision-making more flexible and responsive. Creating multilingual explanations to meet regional language preferences could enhance accessibility and significance. Moreover, using reinforcement learning models could help the system adjust to changing environmental and market conditions. These ideas have the potential to further strengthen the system's reliability, scalability, and user trust, aiding the development of fair and clear AI solutions for precision agriculture in limited-resource settings.

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TECHNICAL SESSION 2

DATA SCIENCE AND THE INTERNET OF THINGS

Automated Timetable Scheduling with a Hybrid Tabu-Heuristic Method

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Abstract—The university timetable generation process is a complex and time-consuming task due to numerous constraints, such as lecture availability, room allocation, and maintaining continuity of laboratory sessions. This paper presents an automated timetable generation system that integrates the Tabu Search metaheuristic with a Probabilistic Constructive Algorithm to efficiently handle these challenges. The proposed hybrid approach combines Tabu Search with a probabilistic fallback mechanism to effectively solve optimization problems. Tabu Search iteratively refines an initial feasible solution by exploring its neighborhood while avoiding revisiting previously explored configurations through the use of a Tabu list. This approach provides an optimal solution within a reasonable computation time, outperforming traditional manual scheduling methods. The system effectively manages complex scheduling tasks involving exams, courses, and laboratory sessions, ensuring efficient resource utilization. This paper demonstrates how combining Tabu Search with probabilistic scheduling principles can yield an optimized and conflict-free academic timetable.

Keywords— Tabu Search, Metaheuristics, Probabilistic Scheduler, Optimization

1. INTRODUCTION

The university timetabling problem is a highly complex scheduling challenge faced by higher education institutions, involving the coordination of courses, laboratory sessions, and examinations. During the scheduling process, various constraints must be considered. In the proposed system, these constraints are classified into two categories: hard constraints and soft constraints. Hard constraints include factors such as room availability, instructor assignment, lecture conflicts, and time management, all of which are mandatory and cannot be violated. Soft constraints, on the other hand, relate to preferences such as specific time slots or days, which can be relaxed within acceptable limits. Since these constraints differ across institutions, manual timetable creation becomes an extremely time-consuming and often impractical process. Human schedulers struggle to manage overlapping requirements and resource limitations efficiently. Therefore, implementing an automated timetable generation system provides a practical and effective solution, significantly minimizing scheduling conflicts and improving overall operational efficiency in academic environments.

2. RESEARCH OBJECTIVE

The proposed system focuses on developing an automated academic timetable system designed to address the persistent scheduling challenges faced by higher education organizations. The process of scheduling a conflict-free timetable is based on constraints and limited resources that affect both students' and the administration's satisfaction. These constraints are divided into Hard constraints and Soft constraints. In our proposed method, complex constraints, which cannot be avoided, are distinguished from soft constraints, which can be avoided through a limited penalty. In this paper, we describe different types of constraints and find an optimized solution.

1) Hard Constraints:
- A faculty member cannot be assigned to two courses and labs simultaneously in the same room.
- A room can only host one activity at one time.
- All activities must fit within defined time slots and credit hours, and lab hours.
- No students batch can have overlapping activities.

2) Soft Constraints:
- Preferred Timing and Days constraints.
- Insufficient activity gaps constraints.
- We must consider faculty preferences sometimes in some special cases

Drawing on research on the effectiveness of the Tabu Search algorithm in scheduling optimization study by Islam et al. [1], this study proposes a hybrid Tabu search framework with the following objectives.

1) Automate conflict-free timetable generation by integrating Tabu Search with advanced neighbor generation and probabilistic scheduling algorithm to effectively schedule throughout given complex constraint spaces.

2) Improve scalability and efficiency of the scheduling process to support large academic institutions.

3) Ensuring compliance with all hard constraints while satisfying soft constraints.

The proposed methodology sections on algorithm design of the hybrid Tabu search algorithm and the probabilistic scheduling algorithm give an overall idea about the concepts and implementation of the system. Finally, the results and analysis section evaluate the effectiveness of the system, utilizing real-world institutional data to assess its effectiveness and scalability within operational academic environments.

3. LITERATURE REVIEW

Various Conferences and journals have been published over the past years on automating timetable scheduling. This work expands on the study by Islam et al. [1]. Who demonstrated the effectiveness of the Tabu Search algorithm for Academic organization timetable scheduling? In this research, our approach extends their method by using a hybrid algorithm to manage complex constraints. Building on Glover's work [2], we adapt the Tabu Search algorithm for time tabling by introducing a combined

metaheuristic optimization with a probabilistic fallback mechanism. Our work introduced specialized neighborhood structure for course and lab scheduling, dynamic Tabu list optimization, and a hybrid approach that ensures both solution optimization and feasibility.

Our research fallback mechanism activates Tabu Search, which reaches a stagnation point [2], utilizing randomized scheduling optimization to ensure a feasible timetable that maintains solution diversity. Adapted from probabilistic scheduling principles [3], this mechanism cyclically managed restricted resources and optimized academic requirements. Optimization of timetabling has been addressed through various algorithms and methods in existing research. Khan and Imtiaz [4] use the genetic algorithm for university timetabling, showing the algorithm's efficiency. In addition, constraint satisfaction techniques [5] and Aron and Abraham [6] demonstrated the effectiveness of greedy heuristic algorithms in scheduling, and these principles are equally applicable for academic timetable optimization.

4. Methodology

Our proposed hybrid timetable system integrates Tabu Search with Probabilistic Recovery to effectively solve the University scheduling problem while satisfying hard constraints and respecting soft constraints. The research proposed an Intelligent Neighborhood design to prioritize high impact moves while striking a strict balance between academic logic. The core logic is Dynamic Tabu Tenure, which balances exploration and exploitation by optimizing memory length based on problem complexity. When Tabu Search stagnation is detected, the system activates a probabilistic fallback mechanism, automatically transitioning while preserving an optimized partial solution to ensure feasibility. This prioritizes hard constraints through a weighted mechanism.

4.1 Tabu Search Algorithm

The Tabu Search metaheuristic algorithm requires structured input to navigate to the optimal solution space effectively. Our system inputs are:

- B = Set of batches {b1, b2, . . . , bn}
- C = Set of courses {c1, c2, . . . , cm}
- L = Set of labs {l1, l2, . . . , lk}
- R = Set of rooms {r1, r2, . . . , rp}
- D = Set of days {d1, d2, . . . , d5}
- T = Set of time slots {t1, t2, . . . , t7}

Decision Variables

- $x_{c,d,t,r} = \begin{cases} 1, & \text{if course } c \text{ is scheduled on day } d \text{ at time } t \text{ in room } r \\ 0, & \text{otherwise} \end{cases}$
- $y_{l,d,t_s,r} = \begin{cases} 1, & \text{if lab } l \text{ starts at time } t_s \text{ on day } d \text{ in room } r \\ 0, & \text{otherwise} \end{cases}$

The variable xc,d,t,r are the assignment of a course c to a specific day d, time slot t, and room r, while the variable yl,d,ts,r shows the start time of a lab session l on day d at time ts in room r.

The Tabu Search algorithm creates an initial scheduling using a greedy method, then iteratively improves this scheduling by exploring small changes. To avoid repeating the exact change and getting stuck, it maintains a Tabu List that temporarily removes recently applied moves. At each step, the algorithm generates a neighboring solution, selects the best moves, updates the Tabu List, and then terminates when a perfect timetable is found. If the algorithm doesn't see an ideal timetable, it retains the partially found timetable and automatically switches to probabilistic scheduling.

Traditional methods only use deterministic moves, but the Tabu Search in this system changes based on how the solution space changes over time. Including a fitness-driven evaluation at each iteration emphasizes the importance of being aware of constraints. It utilizes historical data to make informed decisions and minimize fluctuations by continually refining its approach. The algorithm also employs adaptive tenure control, which adjusts the length of tabu restrictions according to the difficulty of the problem. This makes the system very flexible when it comes to scheduling in the real world. The use of partial repair strategies also allows the algorithm to retain parts that work while improving others. In general, this enhances both convergence speed and scheduling reliability. This kind of flexibility ensures that the method remains scalable and valuable, even in the face of significant scheduling problems with numerous constraints.

Algorithm 1 Tabu Search

```
procedure TABUSEARCH(C, L, R, D, T)
    Input: Courses, Labs, Rooms, Days, Time Slots
    Output: Best solution S*
    S_0 ← CONSTRUCTINITIALSOLUTION, S* ← S_0, TL ← ∅, iter ← 0
    while iter < MAX_ITER ∧ f(S*) > 0 do
        N(S) ← GENERATENEIGHBORHOOD(S)
        S' ← arg min_{S'∈N(S)} {f(S') | move(S → S') ∉ TL ∨ f(S') < f(S*)}
        if f(S') < f(S*) then
            S* ← S', iter ← 0
        else
            iter ← iter + 1
        end if
        UPDATETABULIST(TL, move(S → S'))
        S ← S'
    end while
    return S*
end procedure
```

4.1.1 Neighborhood Generation:

$$N(S) = \bigcup_{c \in C} N_{move}(c) \cup \bigcup_{l \in L} N_{move}(l) \cup \bigcup_{c \in C} N_{swap}(c) \cup \bigcup_{l \in L} N_{swap}(l)$$

Where Nmove(c) denotes all valid moves of course c to new (d, t, r). Nmove(l) denotes all valid moves of lab l to new (d, ts, r). Nswap(c) denotes all valid transfer between course c and other activities.

The Neighborhood Generation algorithm generates a possible adjustment to the current system, enabling the Tabu Search algorithm to evolve. This algorithm systematically

moves courses and labs, then returns all valid variants, like creating a pool of small, feasible adjustments to the current solution, while enabling incremental improvements.

Algorithm 2 Neighborhood Generation

```
function GENERATENEIGHBORHOOD(S)
    N ← ∅
    for all (c, d, t, r) ∈ S.courses do
        for all (d', t', r') ∈ D × T × R_lecture do
            if ISVALIDMOVE(c, d', t', r') then
                S' ← COPY(S)
                S'.MOVE(c, d', t', r')
                N ← N ∪ {S'}
            end if
        end for
    end for
    for all (l, d, t_s, r, h) ∈ S.labs do
        for all (d', t'_s, r') ∈ D × T × R_lab do
            if CHECKCONSECUTIVESLOTS(l, d', t'_s, r', h) then
                S' ← COPY(S)
                S'.MOVE_LAB(l, d', t'_s, r')
                N ← N ∪ {S'}
            end if
        end for
    end for
    return N
end function
```

4.1.2 Fitness Function

$$
\begin{aligned}
f(S) = w_1 \cdot \sum_{c \in \mathcal{C}} \left(\rho_c - \sum_{d,t,r} x_{c,d,t,r} \right)^+ \\
+ w_2 \cdot \sum_{l \in \mathcal{L}} \left(h_l - \sum_{d,t_s,r} y_{l,d,t_s,r} \right)^+ \\
+ w_3 \cdot \sum_{d,t,r} \left(\sum_{c \in \mathcal{C}} x_{c,d,t,r} + \sum_{l \in \mathcal{L}} \sum_{t'=t_s}^{t_s+h_l-1} y_{l,d,t_s,r} \cdot I_{t'=t-1} \right) \\
+ w_4 \cdot \sum_{p \in \mathcal{P}} \sum_{d,t} \left(\sum_{c \in \mathcal{C}(p)} x_{c,d,t,r} + \sum_{l \in \mathcal{L}(p)} \sum_{t'=t_s}^{t_s+h_l-1} y_{l,d,t_s,r} \cdot I_{t'=t-1} \right)
\end{aligned}
$$

Where ρc is the number of credit hours required for course c; hl is the duration of lab l, P is the set of all personnel (lecturers/instructors); wi are the weight parameters, and (x)+ max (x, 0) denotes the positive part of x.

The fitness function f (S) evaluates the quality of a timetable scheduling S by combining four weighted penalty terms that measure constraint violations. (1) missing course sessions (w1), which penalizes when a course's scheduled time is wrong from its required credits ρc. (2) missing lab sessions (w2), granting each lab session l is fully scheduled for its required duration time hl. (3) Room conflicts (w3), detecting overlaps between room usage and (4) Lecturer overloads (w4), preventing the simultaneous operation of any instructor.

Each term uses (x)+ max (x, 0) to count only violations, with weights prioritizing critical issues (e.g., w2 > w1 for lab constraints). The objective is to minimize f (S), where f (S), 0 represents a fully optimized timetable.

4.2 Diversification

The Diversification phase helps the Tabu Search algorithm escape local optima by intentionally disrupting the current solution and generating a new one. In this phase, the system randomly un-scheduling 10% of activities and reschedules them into the earliest valid time slots. This mechanism serves as a restart strategy for the probabilistic scheduling algorithm when it becomes trapped in a local optimum, allowing for the generation of a partial solution that can be further improved and explored.

Algorithm 3 Diversification

```
procedure DIVERSIFY(S)
    /* Unschedule 10% of activities */
    for i ← 1 to ⌈0.1 × (|S.courses| + |S.labs|)⌉ do
        a ← RANDOMSELECT(S.courses ∪ S.labs)
        UNSCHEDULE(S, a)
    end for
    /* Try to reschedule each unscheduled activity */
    for all unscheduled activity a do
        (d, t, r) ← FINDFIRSTVALIDSLOT(a)
        if (d, t, r) ≠ ∅ then
            SCHEDULE(S, a, d, t, r)
        end if
    end for
end procedure
```

4.3 Probabilistic Scheduling

The Probabilistic Scheduling algorithm serves as a backup scheduler when the Tabu Search reaches stagnation. It handles Tabu Search's partial solution and attempts to repair the unscheduled activities using a randomized construction approach. The algorithm prioritizes lab scheduling while satisfying all hard constraints, and then proceeds to randomized course scheduling, also respecting hard constraints. It returns the first generated solution with zero violations, i.e., f (S) = 0. If all attempts fail, the algorithm declares that no solution was found. This method supports recovery from dead ends in Tabu Search and complements the diversification phase as a last-resort constructor. If a valid solution exists that satisfies all hard constraints, the algorithm will eventually find it.

Algorithm 4 ProbabilisticSchedule

```
procedure ProbabilisticSchedule(C, L, R, D, T)
    Input: Courses, Labs, Rooms, Days, Time Slots
    Output: Solution S or failure
    for attempt ← 1 to MAX_ATTEMPTS do
        S ← EmptySolution, L' ← RandomPermutation(L), success ← true
        for all l ∈ L' do
            (d, t_s, r) ← FindConsecutiveSlots(l, R, D, T)
            if (d, t_s, r) = ∅ then
                success ← false; break
            end if
            ScheduleLab(S, l, d, t_s, r)
        end for
        if not success then
            continue
        end if
        C' ← RandomPermutation(C)
        for all c ∈ C' do
            (d, t, r) ← FindAvailableSlot(c, R, D, T)
            if (d, t, r) = ∅ then
                success ← false; break
            end if
            ScheduleCourse(S, c, d, t, r)
        end for
        if success and f(S) = 0 then
            return S
        end if
    end for
    return "No feasible solution found"
end procedure
```

4.4 Web Interface and System Architecture

To ensure the practical usability of the proposed scheduling system, a web-based interface was developed to simplify data entry, scheduling execution, and results visualization. The interface provides a bridge between the end user (academic administrators or scheduling officers) and the underlying Hybrid Tabu-Probabilistic scheduling engine.

1) System Overview: The system is designed as a client–server architecture, where the client interface runs on a standard web browser and communicates with the backend scheduling engine hosted on a web server. The backend implements the core algorithms—Tabu Search, probabilistic fallback, and fitness evaluation—while the front end manages user interaction and file handling.

2) User Workflow: The workflow of the system is illustrated as follows:

I. Template Download: Users begin by downloading a pre-formatted Excel template from the web interface. This template includes structured fields for inputting essential data such as batch names, lecturers, rooms, laboratory sessions, and time slots.

II. Data Entry: The administrator fills in all relevant details in the Excel sheet according to the institution's scheduling requirements. This spreadsheet format ensures data consistency and ease of use without requiring technical expertise.

III. File Upload: Once completed, the Excel sheet is uploaded through the web interface. The backend server automatically parses the uploaded file, validates its structure, and converts the data into a format compatible with the scheduling algorithms.

IV. Timetable Generation: After successful validation, the user can initiate the scheduling process by clicking the "Generate Timetable" button. The hybrid Tabu-Probabilistic engine is then executed on the server to compute an optimized timetable while satisfying all defined hard and soft constraints.

V. Timetable Download: Upon completion, the generated timetable is automatically exported as an Excel file and made available for download. The resulting file follows the same structured format, containing all course, room, and lecturer allocations, ensuring easy verification and printing for official use.

3) Implementation Details: The front end was developed using HTML, CSS, and JavaScript to ensure responsive and user-friendly interaction. At the same time, the backend was implemented using Python (Flask/Django) to handle scheduling requests, data validation, and Excel file operations. The scheduling algorithms were modularized, enabling future extension for additional features such as automatic conflict detection, semester-wise filtering, and integration with Learning Management Systems (LMS).

4) Usability and Practical Benefits: The web interface allows non-technical users to perform complex scheduling tasks through a simple, guided workflow. By supporting Excel-based data import and export, the system reduces the learning curve for first-time users and minimizes manual data entry errors. It also enables centralized access, allowing multiple departments across campuses to submit their data and retrieve generated timetables simultaneously.

This architecture enhances scalability, accessibility, and transparency—key elements in ensuring the system's real-world applicability and adoption in university environments.

5. RESULT AND ANALYSIS

Our Tabu Search and Probabilistic scheduling algorithm successfully generated an optimized scheduling system, achieving a perfect fitness score of 0 while maintaining efficient computational performance. The algorithm's success stems from its innovative Neighboring Generation and adaptive Tabu Search, along with a Probabilistic scheduling recovery mechanism. Notably, our dynamic tabu tenure system and fallback mechanism demonstrate the ability to resolve complex, real-world constraints. Notably, our proposed dynamic tabu tenure system shows how to address challenging real-world constraints, particularly the complex problem of allocating uninterrupted, consecutive time periods for lab sessions. An accurate distribution of the hours needed for their assigned credit weight. Additionally, this approach has no penalty and satisfies all soft constraints.

5.1 Fitness Comparison Across Batches

The Fitness Comparison of Different Batches (Figure 1) indicates that our proposed algorithm achieved a perfect fitness score (0) for all batches, which means that aour algorithm eliminates all constraint vitalization Unlike manual scheduling, which

struggles with specific batch constraints, our proposed method optimizes course hours (w1 = 0), incomplete lab sessions (w2 = 0), and room and lecturer conflicts (w3 = w4 = 0). This consistency demonstrates the system's reliability across various academic requirements.

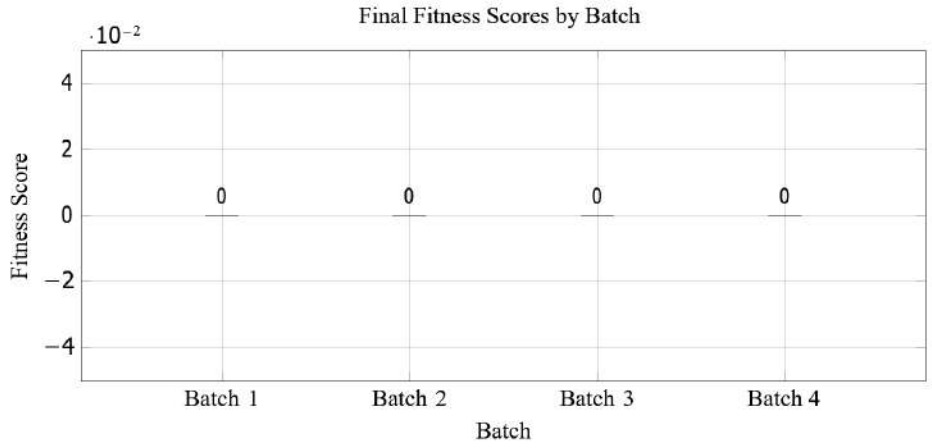

Fig. 1: Fitness Comparison of Different Batches

5.2 Distribution of Fitness Values Over Search Space

The fitness distribution plot (Figure 2) demonstrated that the final fitness value was 0 in the 100% all evaluated runs. This sharp peak indicates the absence of suboptimal outcomes at the end of our process, implying that all imposed conditions are fully met with our proposed system. This outcome provides strong evidence of the algorithm's optimal performance across multiple executions and its ability to escape local optima, ultimately confirming the algorithm's effectiveness in finding globally optimal and optimized solutions.

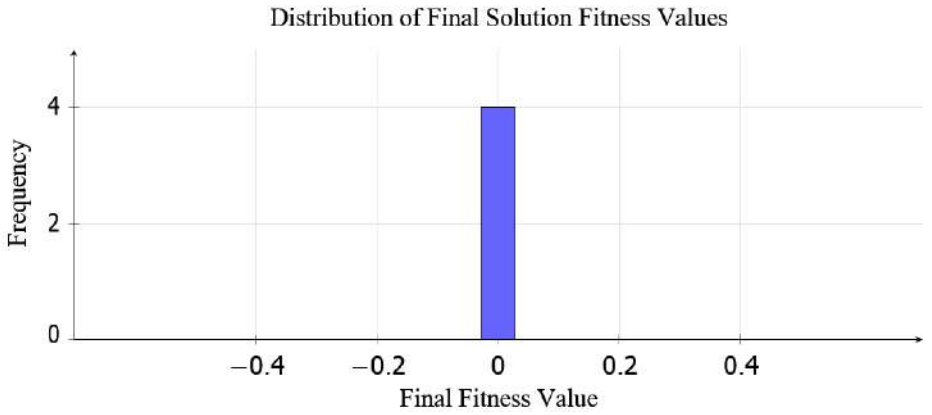

Fig. 2: Distribution of Fitness Values Over the Search Space

5.3 Penalty Component Breakdown

The batch-wise penalty breakdown demonstrates that all components, unscheduled courses (w1), unscheduled labs (w2), lecturer conflicts (w3), instructor conflicts (w4), and unavailable days (w5), were reduced to zero penalties across all batches. Particularly, lab-related penalties (w2), which highly contribute to the penalty scores, indicate overall effectiveness in algorithmic advancement. Furthermore, it claims that all soft constraints were simultaneously satisfied. This result confirms the suitability of the chosen weighting strategy, prioritization hierarchy w2 > w1 > w3 > w4 > w5, which prioritized critical soft constraints, such as unscheduled labs, while ensuring a feasible solution across all dimensions.

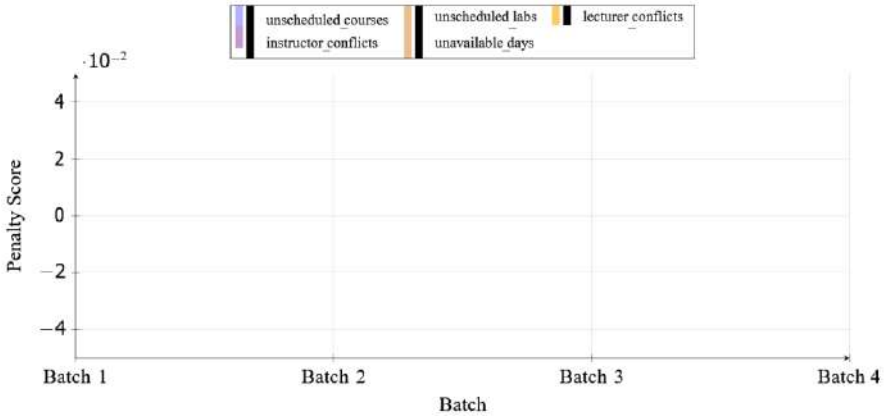

Fig. 3: Penalty Component Breakdown Across Each Batch

5.4 Iteration Analysis Over Problem Space

The iteration analysis over the problem space in Figure 4 demonstrates that an effective optimization of the scheduled timetable was achieved early on, as indicated by zero penalty values over all batches. Fitness improvements are clearly noted in all four batches, indicating zero fitness value as the best fitness value. Neighbor generation fluctuates when aligning with fitness gain. Tabu list grows steadily and reaches a stable point, reflecting total control over diversification and cycling. Overall, the proposed algorithm demonstrates strong performance in handling constraints and optimizing the scheduling process, with room for improvement in handling more complex problem spaces.

5.5 Runtime Analysis Over Problem Space

The Hybrid Tabu-Heuristic algorithm was implemented and executed on an Intel® Celeron® N4000 CPU operating at 1.10 GHz. Despite the modest computational capability of this processor, the algorithm demonstrated efficient convergence with minimal computational overhead. A total of 63 iterations were conducted across four independent batches, yielding an average final fitness value of 23.75 and a best fitness value of 0, which indicates the successful generation of conflict-free timetables in

optimal runs. The total execution time recorded for the complete process was 0.39 seconds, highlighting the algorithm's lightweight design and high efficiency, even when executed on low-power hardware.

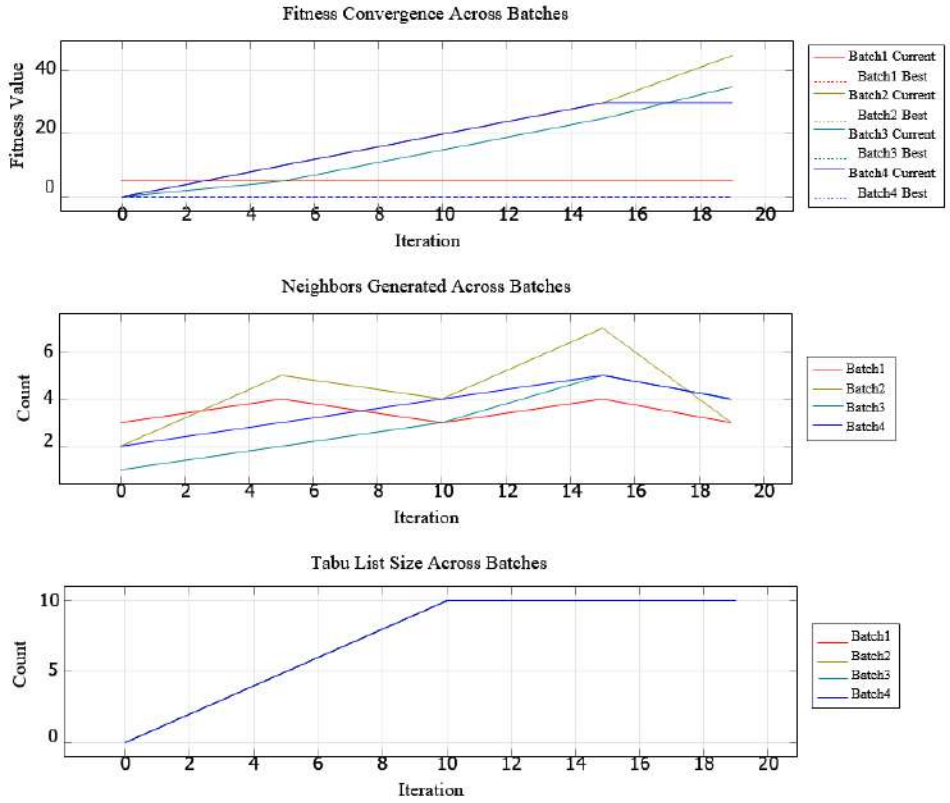

Fig. 4: Performance metrics of the Tabu Search across all four batches

5.6 Comparative Analysis with GA and SA

To evaluate the relative performance of the proposed Hybrid Tabu-Heuristic algorithm, a comparative study was conducted against two classical metaheuristic techniques: the Genetic Algorithm (GA) and Simulated Annealing (SA). Each algorithm was executed under identical experimental conditions, ensuring a fair evaluation of computational efficiency and solution quality. The comparison metrics include execution time, average fitness, and solution feasibility, as summarized in Table I.

Table I: Comparison of Tabu-Heuristic, Genetic Algorithm, and Simulated Annealing

Algorithm	Success	Time (s)	Avg. Fitness	Perfect Sol.	Course (%)	Lab (%)	Overall (%)
Tabu-Heuristic	Yes	0.34	0	4	100	100	100
Genetic Algorithm	Yes	0.94	0	4	100	100	100
Simulated Annealing	Yes	1.57	0	4	100	100	100

The results indicate that all three algorithms successfully generated conflict-free timetables with identical completion and feasibility rates. However, the proposed Hybrid Tabu-Heuristic algorithm demonstrated a substantial improve- ment in computational efficiency, achieving the lowest execution time of 0.34 seconds, which is approximately 63.8% faster than the Genetic Algorithm and 78.3% faster than Simulated Annealing. This efficiency gain underscores the lightweight design and faster convergence behavior of the Tabu-Heuristic method, making it particularly suitable for deployment on low-power or resource-constrained computing environments.

5.7 Performance Evaluation Under High-Stress Configuration

To further evaluate the robustness of the proposed Hybrid Tabu-Heuristic algorithm, a high-stress scheduling scenario was simulated. The test environment included a total of 10 laboratory sessions and 15 course modules distributed across four batches of students within a single semester. The available resources were intentionally limited to only two lecture rooms and three laboratory rooms, creating a dense and highly constrained scheduling space. Despite this resource limitation and elevated constraint load, the algorithm consistently achieved an optimal fitness score of 0, indicating complete satisfaction of all hard and soft constraints. Correspondingly, all penalty components were reduced to zero, confirming that no scheduling conflicts or violations occurred. This outcome demonstrates the strong capability of the algorithm to maintain the feasibility of the solution and optimization performance even under high-demand scheduling conditions.

6. COST–BENEFIT ANALYSIS

The integration of a Hybrid Tabu–Heuristic Scheduling System with a web-based interface provides a practical and scalable solution to the complex problem of university timetable generation. This section evaluates the financial, operational, and institutional implications of deploying the system in real-world university environments.

6.1 Cost Analysis

The primary cost factors involve system development, server deployment, data integration, and staff training. The initial setup requires configuring the system to accommodate institutional parameters such as course structures, laboratory sessions, and academic calendars. Since the proposed system operates through a web interface, only minimal hardware infrastructure is required—typically a central web server and standard web browsers—making it cost-effective for universities.

Integration with existing academic management systems may involve a one-time data migration and user-access configuration. Additionally, the design of Excel-based templates requires institutional customization to match different faculty structures and course distributions. Training sessions for academic and administrative users are essential to ensure efficient use of the interface, file uploading, and verification of generated schedules.

Despite these setup requirements, the system substantially reduces long-term administrative overhead, eliminating repetitive manual scheduling and reducing

dependency on multiple staff members. Once operational, only minimal maintenance—such as updating course data or semester information—is required.

6.2. Benefit Analysis

The proposed system delivers multiple layers of benefits across operational, academic, and strategic dimensions.

1. Enhanced Efficiency and Accuracy: The hybrid Tabu-Probabilistic algorithm generates conflict-free timeta- bles within minutes, significantly reducing the time and effort required for manual preparation. The algorithm ensures high accuracy by automatically enforcing hard constraints (such as room and faculty conflicts) while accommodating soft constraints such as faculty preferences and preferred teaching hours.

2. User-Friendly Web Interface: The inclusion of a web-based interface greatly improves usability. Through an intuitive workflow, users can download a structured Excel template, input all scheduling details, upload the file, and generate a complete timetable automatically. The downloadable Excel output allows users to verify and share results immediately without additional software. This approach minimizes human error and lowers the learning curve, enabling non-technical users to operate the system efficiently.

3. Scalability for Multi-Campus Institutions: The system architecture supports multi-campus scheduling by allowing each campus to upload its dataset separately. The backend algorithm synchronizes all inputs to generate an integrated master timetable while ensuring inter-campus resource allocation and instructor distribution are optimized. This makes the system suitable for universities with multiple branches or faculties operating under a shared timetable policy.

4. Dynamic Updates and Real-Time Adjustments: Real-world academic operations often face unexpected changes, such as instructor leave, room maintenance, or additional course sections. The system supports incremental scheduling updates, allowing partial modifications without regenerating the entire timetable. This flexibility ensures continuity in academic operations and minimizes disruption when unforeseen changes occur.

5. Institutional Transparency and Collaboration: Every schedule generated by the system can be traced and justified, enhancing transparency in course and room allocation. The web interface also facilitates multi- user collaboration, allowing department heads, administrators, and lecturers to review or propose updates simultaneously from different locations.

6. Strategic Long-Term Benefits: Over successive semesters, the accumulated scheduling data can be analyzed to predict resource utilization trends, identify bottlenecks, and optimize future academic planning. The consistent use of the system contributes to data-driven decision-making, enhancing institutional productivity and strategic resource management.

6.3 Limitations and Mitigation Strategies

Although the system effectively addresses complex scheduling challenges, several deployment challenges remain. These include differences in faculty policies across campuses, the need to periodically update input templates, and occasional resistance from users accustomed to manual processes. These challenges can be mitigated through:

• Providing comprehensive user training and ongoing technical support.

• Implementing feedback loops to refine interface usability; and

• Performing quarterly algorithm tuning to handle evolving constraints and data volumes.

6.4 Overall Assessment

The Hybrid Tabu–Heuristic Timetable Scheduling System, combined with a web-based interface, offers a high return on investment for educational institutions. While the initial setup involves moderate costs for configuration and user training, the resulting improvements in accuracy, efficiency, and adaptability significantly outweigh these expenses.

The system's ability to incorporate user preferences, operate in multi-campus environments, and support dynamic updates establishes it as a robust and scalable solution for modern academic scheduling needs.

7. CONCLUSION

The university timetable generator creates schedules that avoid conflicts by employing a proposed hybrid Tabu- heuristic method that optimizes resource utilization. This method reduces the amount of manual work required. There are some initial setup and training requirements, but in the long run, productivity increases and administrative tasks become easier, ultimately benefiting everyone.

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Optimizing Order Wait Times in a University Canteen Using Data Structures

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Abstract—Efficiently managing queues for main meals in university canteens is a practical yet often overlooked challenge. This paper explores how various data structures and scheduling algorithms influence customer wait times in a simulated canteen environment. We implement and evaluate First-In-First-Out, Random Selection, Shortest Job First, and Priority Queue with Aging strategies. Additionally, we integrate a predictive model using linear regression to dynamically adapt queue strategies based on expected order influx. The results show that the Aging Priority Queue offers the best trade-off between efficiency and fairness, reducing average wait times by 42.66% compared to Random, 17.61% compared to FIFO, and 38.88% compared to SJF (Min-Heap). Even though this study focuses on a university canteen, the same approach can be applied to optimizing queues in a wide range of real-world scenarios.

Keywords—Predictive Modeling, Queuing Strategies, Scheduling Algorithms, Priority Queue with Aging, Shortest Job First

1. INTRODUCTION

University canteens often face high congestion during peak hours, particularly lunch. Few cooks preparing meals sequentially without strategy can result in long, unfair wait times. This project simulates real-time order handling using different data structures and introduces a predictive component to enhance efficiency. By focusing on a Sri Lankan public university environment, we demonstrate local relevance and practical applicability.

Simulation of queueing systems has gained increasing attention for optimizing service efficiency in real-world settings, though it remains relatively underexplored. Nsude et al. [1] analyzed multiple-server queuing models by presenting the mathematical underpinnings of arrival and service time distributions and proposed optimal server counts to balance cost and idle time. Aqil [2] applied Arena simulation to a local cafeteria, determining ideal resource allocation by adjusting barista count and seating to improve customer flow while minimizing operational cost. Similarly, Sanjay et al. [3] demonstrated through discrete event simulation that performance in a student canteen could be enhanced by simply adding an extra server, with further improvements suggested by reorganizing coupon and menu access methods.

Other researchers have focused on customer behavior and overall service time. Dharmawirya et al. [4] compared expected versus actual wait times in fast-food restaurants, finding that average customer wait during lunch rushes reached 5.4

minutes, with speed, price, and cleanliness being top customer priorities. Chou and Liu [5] showed that wait time in Taiwanese fast-food outlets could be reduced by recruiting additional staff during peak hours. Curtin et al. [6] analyzed a high-traffic campus restaurant and found that a five-person team with task-specific roles significantly reduced customer system time, and even recommended a dual-purpose server for further efficiency. These studies consistently highlight two dominant strategies—adding service counters and better utilizing existing resources—as foundational for improving queue performance. Our project builds on these insights by combining simulation with predictive modeling to address congestion in a Sri Lankan university canteen.

Our goal is to model a university canteen environment where a cook handles incoming orders during a lunch rush. The aim of this project is to reduce the overall waiting time experienced by students in the university canteen. This involves minimizing three key metrics: the total wait time, which represents the cumulative waiting time of all customers; the average wait time, which reflects how long a typical customer waits before receiving their meal; and the maximum wait time, which indicates the longest individual delay encountered. To accomplish this, the project employs efficient scheduling algorithms that determine the sequence of order processing and integrates predictive modeling to forecast order patterns, allowing the system to dynamically adapt and improve queue management.

2. METHODOLOGY

2.1 Dataset Overview

We simulate a canteen environment with 25 random orders, each having an arrival_time between 720 and 750 minutes (12:00–12:30 PM), and a prep_time between 1 and 7 minutes. Each order is stored as a dictionary containing metadata such as ID, arrival time, prep time, start and end time, and wait time.

TABLE I: Sample of 25 Simulated Canteen Orders

Order ID	Arrival Time (min)	Prep Time (min)
07	720	5
01	720	7
23	720	2
12	723	6
15	725	7
02	727	6
08	728	4
13	728	7
20	728	3
05	729	3
17	729	5
04	734	1
11	734	5
19	737	7
24	738	2

03	740	5
16	741	3
21	742	6
06	743	6
09	744	2
14	744	6
22	746	5
25	747	3
10	748	5
18	750	5

2.2 Order Simulation

We simulate each order minute by minute in a discrete-time loop from 720 to 780 (1 hour duration). New orders are added based on their arrival times, and the cook processes them based on the selected scheduling strategy.

```
def generate_orders(num_orders=25):
    orders = []
    for i in range(1, num_orders + 1):
        arrival_time = random.randint(720, 750)
        prep_time    = random.randint(1, 7)
        orders.append({
            'id': i,
            'arrival_time': arrival_time,
            'prep_time': prep_time,
            'start_time': None,
            'end_time': None,
            'wait_time': None
        })
    return sorted(orders, key=lambda x: x['arrival_time'])
```

Fig. 1: Order generation function

2.3 Simulation Assumptions and Parameters

We model a single-server canteen during the lunch window using a discrete-time clock.

• Clock and horizon. Time is measured in minutes; the simulation runs from 12:00 to 13:00 (minutes 720–780).

• Server model. One cook processes one order at a time; service is non-preemptive (a job, once started, runs to completion). Queue capacity is unbounded; arrivals always join.

• Service times. Preparation times are discrete and uniformly sampled from {1, 2, . . . , 7} minutes.

• Dispatch events. The scheduler selects the next order only when the cook becomes idle. New arrivals during service wait in the queue.

• Predictive model data. For the regression baseline, we generate synthetic history of 10 days with 25 orders/day using the same arrival and service distributions (no real data used).

• Applicability. These assumptions apply to all evaluated methods—FIFO, Random, SJF, and Aging; only the dispatch rule differs.

2.4 Queueing Strategies Implemented

1) FIFO (First-In-First-Out): FIFO uses a simple queue structure (in Python, a deque) to serve the earliest arriving order first. This approach guarantees that every order is processed in the order it was received, ensuring no task is ever skipped or starved, and both insertion and removal execute in constant time. On the downside, longer or more complex orders at the front can delay all subsequent requests, increasing the overall average wait time. Despite this, its straightforward implementation and clear fairness properties make FIFO a valuable baseline for comparing more advanced scheduling strategies.

```
from collections import deque

queue = deque()
# ...
if current_time >= cook_busy_until and queue:
    current_order = queue.popleft()
    current_order['start_time'] = current_time
    current_order['end_time']   = current_time + current_order['prep_time']
    current_order['wait_time']  = current_time - current_order['arrival_time']
    completed_orders.append(current_order)
```

Fig. 2: FIFO processing snippet

2) Random Selection: Random Selection picks one waiting order uniformly at random each time the cook becomes available. Its simplicity means almost no decision logic is required, but without any priority or arrival- order constraints, wait times become highly variable: some orders may go straight to service while others experience long delays. Consequently, average and maximum wait times are generally higher and less predictable than with structured policies.

```
import random

if current_time >= cook_busy_until and queue:
    current_order = random.choice(queue)
    queue.remove(current_order)
    current_order['start_time'] = current_time
    current_order['end_time']   = current_time + current_order['prep_time']
    current_order['wait_time']  = current_time - current_order['arrival_time']
    completed_orders.append(current_order)
```

Fig. 3: Random selection snippet

3) SJF (Shortest Job First): SJF (Shortest Job First) uses a min-heap to always pick the order with the smallest remaining prep time next. By prioritizing the quickest tasks, it achieves the lowest possible average wait time under non-preemptive scheduling. However, without safeguards, long orders can be repeatedly delayed if shorter ones keep arriving, leading to potential starvation. Despite this drawback, SJF is widely studied and serves as a benchmark for assessing the efficiency of more advanced, fairness-aware algorithms.

```
import heapq

heap = []
# ...
heapq.heappush(heap, (order['prep_time'], order['id'], order))
_, _, current_order = heapq.heappop(heap)
# set start_time, end_time, wait_time...
```

Fig. 4: SJF using min-heap snippet

4) Priority Queue with Aging: The Aging policy is designed to keep SJF-like efficiency while avoiding starvation. It favors short jobs but steadily boosts the priority of any order that has waited a long time, so older jobs eventually rise to the top. Concretely, at each dispatch instant (when the cook becomes idle) we recompute a score for every waiting order that discounts its preparation time by a small amount proportional to its current wait:

$$\text{score}_i(t) = \text{prep time}_i - \alpha(t - \text{arrival time}_i),$$

where $\alpha > 0$ is a dimensionless aging weight. Lower scores are selected first, so short jobs tend to win, but prolonged waiting decreases a job's score and prevents starvation.

Value used: All experiments use $\alpha = 0.10$ unless otherwise stated. This value was chosen empirically from pilot runs to balance mean and maximum wait time. Scores are recomputed for all waiting jobs only when the cook becomes idle, then the job with the lowest score is selected.

```
for order in waiting_orders:
    wait_time      = current_time - order['arrival_time']
    priority_score = order['prep_time'] - aging_factor * wait_time
    heapq.heappush(heap, (priority_score, order['id'], order))
_, _, current_order = heapq.heappop(heap)
# set start_time, end_time, wait_time...
```

Fig. 5: Priority queue with aging snippet

2.5 Predictive Modeling

We trained a Linear Regression model using historical data (10 days×25 orders/day) to predict prep times from arrival times.

```
from sklearn.linear_model import LinearRegression
from sklearn.model_selection import train_test_split

# Build dataset
X = historical_df[['arrival_time']]
y = historical_df['prep_time']
X_train, X_test, y_train, y_test = train_test_split(
    X, y, test_size=0.2, random_state=42)

# Train model
model = LinearRegression()
model.fit(X_train, y_train)

# Predict
new_X = pd.DataFrame({'arrival_time': [o['arrival_time'] for o in new_orders]})
preds = model.predict(new_X)
```

Fig. 6: Linear regression training snippet

These predictions allow dynamic adaptation of queue strategies based on expected workloads.

2.6 Visualization and Evaluation

We plotted average and maximum wait times for all strategies using matplotlib:

```
import matplotlib.pyplot as plt

plt.figure(figsize=(8,4))
plt.bar(strategies, avg_waits)
plt.title("Average Wait Time by Strategy")
plt.xlabel("Strategy")
```

Fig. 7: Visualization snippet

2.7 Algorithmic Complexity

We analyze both the time per decision (enqueue, dequeue, select) and the overall space requirements for each queueing strategy. Table II summarizes these costs for a queue of size n.

TABLE II: Algorithmic Complexity of Queueing Strategies

Strategy	Time per Operation	Space Complexity
FIFO	$O(1)$ enqueue/dequeue	$O(n)$
Random	$O(1)$ pick, $O(n)$ remove	$O(n)$
SJF	$O(\log n)$ push/pop in heap	$O(n)$
Aging	$O(n + \log n)$ rebuild heap	$O(n)$

Our observations indicate that:

• FIFO operations run in constant time, making it very efficient on the algorithmic side—but it does not prioritize shorter jobs.

• Random selection requires constant time to choose an index but linear time to remove that element from the list, leading to an O(n) worst-case per decision.

• SJF uses a binary heap: each insertion or extraction is O(log n), so total simulation cost is O(n log n).

• Priority with Aging must recompute priorities for all m waiting orders (up to n), rebuild a heap in O(m), then extract in O(log m), giving O(n + log n) per service decision.

Compared to SJF, the Aging strategy pays a linear overhead to guarantee no starvation, which remains practical for typical canteen queue sizes (e.g., n ≤ 100).

3. RESULTS AND ANALYSIS

Table III summarizes the performance metrics

TABLE III: Performance Comparison of Strategies

Strategy	Avg Wait (min)	Max Wait (min)
FIFO	26.12	71
Random	37.52	86
SJF	35.20	68
Priority Aging	21.52	58

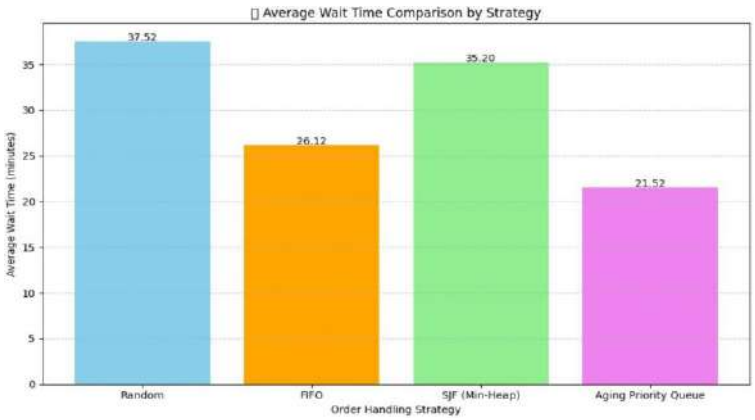

Fig. 8: Average Wait Time Comparison by Strategy

The simulation results reveal that each scheduling strategy impacts customer wait times differently. FIFO (First- In-First-Out) is fair but inefficient, resulting in a total wait time of 948 minutes, an average wait of 26.12 minutes, and a maximum wait of 71 minutes. Random Selection yielded slightly better total wait times (890 minutes) but with a significantly higher average wait of 37.52 minutes and a maximum wait of 86 minutes, making it unpredictable and inconsistent.

Shortest Job First (SJF) improved total wait time to 499 minutes and offered a moderate average wait of 35.20 minutes with a maximum of 68 minutes. However, it risks starving larger orders due to its bias toward short preparation tasks. The Priority Queue with Aging strategy demonstrated the best balance, achieving the lowest total wait time of 451 minutes, the lowest average wait time of 21.52 minutes, and a maximum wait of 58 minutes. This method effectively reduces delays while preventing starvation, making it the most optimal among the evaluated strategies.

4. LIMITATIONS AND THREATS TO VALIDITY

• Synthetic data: Experiments use simulated arrivals (uniform over 12:00–12:30) and discrete service times in

{1, . . . , 7} minutes. Real canteens may show bursty demand, menu-dependent prep times, batch cooking, and setup/cleanup overheads not captured here.

• Single-server, non-preemptive model: We assume one cook, non-preemptive service (jobs run to completion), and an unbounded queue. Multiple cooks, preemption, or finite buffers could change relative performance.

• Scale and horizon: Results are for a modest setting (N = 25 orders within 60 minutes). Larger systems or longer horizons may alter both averages and tail (max) behaviors.

• Predictive component: The regression is a simple linear model trained on synthetic history; richer time-series features and real transaction logs are likely to improve adaptation and calibration.

• Statistical reporting: We primarily report representative point estimates. Future work should include replicated runs with confidence intervals and sensitivity analyses (e.g., varying α, arrival/service distributions, and tie-breaking rules).

5. CONCLUSION

In this paper, we have presented a comprehensive simulation study of four different queueing strategies—FIFO, Random Selection, SJF, and Priority Queue with Aging—in a university canteen setting. By generating 25 random orders per run and measuring total, average, and maximum wait times, we showed that:

• SJF has high wait time (35.20min) but risks starvation for larger orders.

• FIFO and Random Selection are simple to implement but yield substantially higher average delays (26.12min and 37.52min, respectively).

• Priority Queue with Aging strikes the best balance, reducing average wait to 21.52min while guaranteeing no order waits indefinitely.

Moreover, by training a linear regression model on five days of historical order patterns, we demonstrated how predictive insights can be fed back into strategy selection to anticipate demand and further reduce delays. Overall, our work highlights the power of combining classical data-structure algorithms with lightweight machine learning to optimize real-world service processes.

6. FUTURE WORK

While our simulation framework provides a solid proof of concept, there are several promising directions for further development:

• Multi-Cook Simulations: Extend the model to multiple cooks working in parallel, exploring load-balancing and task-splitting heuristics.

• Real-World Data Integration: Incorporate actual canteen transaction logs (e.g., timestamps, menu mix) to validate and refine both the simulation parameters and the predictive model.

• Dynamic Pricing and Priority Levels: Investigate how differential pricing or customer-declared urgency levels can be used to further optimize fairness and revenue.

• Advanced Predictive Models: Experiment with more expressive models (e.g., decision trees, time-series forecasting) to capture non-linear demand patterns and special-event spikes.

• User-Facing Prototype: Develop a mobile/web application that allows customers to view estimated wait times in real time, collect feedback, and adjust queue priorities dynamically.

• Robustness and Sensitivity Analysis: Perform sensitivity studies on arrival distributions, prep-time variability, and aging factors to assess the stability of each strategy under stress conditions.

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Scrap Wise: Real-Time Metal vs Non-Metal Classifier Using Sensor Fusion

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Abstract—This paper presents a system that separates metals and non-metals automatically, which prevents manual contact with contaminated materials. This system uses an ultrasonic sensor that measures the distance to detect an object and an inductive proximity sensor, both controlled by an Arduino board, to identify metallic objects and classify materials. In simple terms, the system detects an object, identifies its type through the sensors, and directs it into the appropriate bin using servo motors. The design focuses on low power usage and easy operation. During testing, this system successfully reached a 92% success rate. It worked well for metals like steel and iron, as well as non-metals such as paper, plastic, and rubber. The results show that a compact, low-cost system can still perform reliable waste sorting. Future work will include improving detection for non-ferrous metals, adding solar power, and extending sorting into more categories.

Keywords—Arduino system, Metal detection, Non-metal detection, Sensor-based automation, Waste sorting

1. INTRODUCTION

Waste separation helps to bridge the gap between the natural and built environments. However, in many developing countries, this waste separation is carried out manually, which risks the sanitary workers' health and the environmental balance. Moreover, it slows the process, is inefficient, and increases expenses. As a solution, an automated waste sorting system can be introduced [1].

To address this, many researchers have developed systems that can separate waste materials using computer vision, IoT, and machine learning [1], [2], [3], [5]. Although these systems are accurate, they require high power and are expensive because they rely on costly hardware [2], [6]. As a result, many countries are unable to implement automatic waste sorting systems [3], [6], [8].

Therefore, there is a need for a low-cost, energy-efficient system that can automate waste sorting in resource-limited settings. This study presents a low-cost, energy-efficient system that separates metals and non-metals using a simple sensor fusion technique that combines an ultrasonic sensor and an inductive proximity sensor. These sensors are monitored through the Arduino microcontroller, which facilitates the waste sorting process, with the main goal of achieving reliable accuracy using minimal hardware, making it easily applicable in local waste management and educational settings. The main objective of this study is to design, develop, and validate a low-cost, Arduino-based sensor fusion prototype capable of classifying metal and non-metal waste in real time

with over 90% detection accuracy. Existing waste sorting technologies tend to be expensive and energy-intensive, making them unsuitable for use in low-resource settings. Thus, the potential of simple sensor fusion, replicable at a low cost, is under-researched regarding whether it can provide the same level of accuracy without the need for high-cost systems. Therefore, the presented study has the following objectives:

- To develop the low-cost and energy-efficient waste classifier that uses ultrasonic and inductive sensors.
- To assess its accuracy in metal and non-metal identification.
- To assess its performance compared to existing waste isolation models.

This study directly supports the low-hanging fruit in low-cost sensing and takes a close look at the feasibility of ultrasonic–inductive sensor fusion for real-time material classification, which has largely been ignored by prior work.

2. METHODOLOGY

The methodology of the project outlines the step-by-step procedure adopted for designing, developing, and deploying an automated waste separation system which can distinguish between metal and non-metal materials on the basis of sensor fusion. As illustrated in Fig. 1, the operational process begins with detection by the ultrasonic sensor, followed by confirmation through the inductive proximity sensor. Based on this classification, the RG996R servo motor directs the waste to the appropriate bin. Subsequently, the RG90 servo motor actuates to deposit the waste into the corresponding collection bin.

2.1 Waste placement and start of detection

When the waste is poured into the small bin atop the larger one, it will be detected and will then start the sorting procedures.

2.2 Ultrasonic sensor detection

The ultrasonic sensor is the first sensor used in the detection mechanism. When ultrasonic waves are emitted, the time it takes for scattered waves to return gives a distance calculation. This step is to confirm that the next machine can operate only when an object has been detected nearby. The ultrasonic sensor was chosen because it allows measuring distance, regardless of the color or reflectivity of the object, which contributes to creating a sensor fusion to enhance the consistency of object detection.

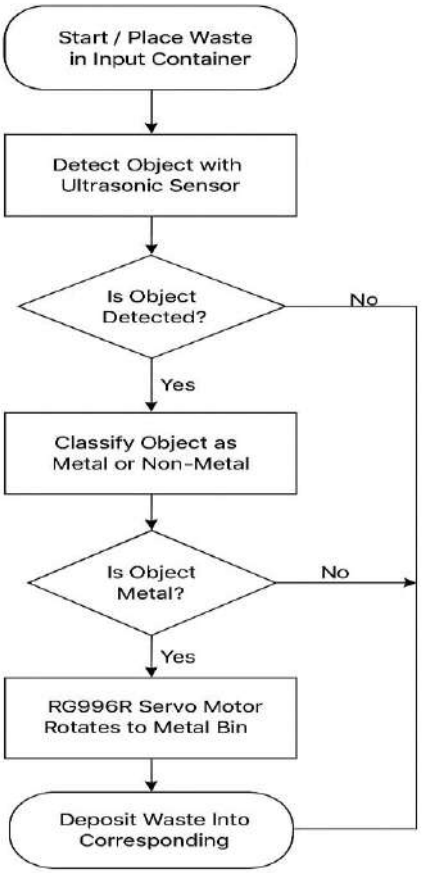

Fig. 1. Block diagram of the automated waste segregation system.

2.3 Induction proximity sensor test

When material is present, the inductive type proximity sensor activates and detects metallic materials automatically. It picks up electromagnetic field disturbances as metal materials, by adjusting a ferrite core within an induction coil. If the field is broken, it is identified as metal; if not, then it is classified as non-metal. The inductive proximity sensor was also selected due to its high sensitivity to ferromagnetic metals and a simple low-cost implementation compared to the use of more complex metal detectors.

2.4 Classification Decision

After receiving the signal from the inductive sensor, the RG996R servo motor rotates the actuator toward the appropriate bin. If the object is judged to be metal, then it goes into metal bin; otherwise, it goes into the non-metal bin.

2.5 Dropping Waste Cycle Using RG90 Servo

Next, the RG90 servo motor is activated, extending from the small bin containing all the waste. Its lifting or flapping motion drives waste material into the suitable bin and cuts power to the motor. As a result, the trash falls smoothly without getting stuck in the small bin, which prevents the waste from mixing. Moreover, this ensures a consistent, uninterrupted flow of waste.

2.6 End Cycle & Reset

Once the entire process is complete, the sorter returns to its original state. Soon after reset, it will be ready for the next sorting process. This cycle makes it possible to perform real-time waste sorting in household or industrial conditions continuously.

Fig. 2. Sorting mechanism of the waste classifier

3. RESULTS AND DISCUSSION

This model has achieved a success rate of nearly 92%, which is consistent with findings from similar smart waste segregation systems [1]. The table below presents the results of our testing, and Fig. 3 illustrates the detection accuracy for the tested materials. Green bars represent successful detections (≥80%), while red bars represent materials that were detected less effectively.

TABLE I. Detection Status, Accuracy, and Sensor-Based Reasoning for Each Material

Material	Detection Status	Accuracy (%)	Reason for Detection / Non-Detection
Steel	Detected	100%	Strongly magnetic; high conductivity; easily detected by inductive sensor

Iron	Detected	100%	Ferromagnetic; easily detected by inductive sensor
Paper	Detected	95%	Non-metal; dielectric properties influence sensor
Rubber	Detected	90%	Non-metal; minor sensor response allows detection
Plastic	Not Detected	15%	Non-ferrous; inductive sensor cannot detect effectively
Copper	Not Detected	10%	Non-magnetic; low conductivity at sensor frequency
Aluminum	Not Detected	5%	Non-ferrous alloy; sensor cannot detect
Brass	Not Detected	8%	Alloy with low magnetic permeability; weak sensor response
Bronze	Not Detected	5%	Non-ferrous alloy; sensor cannot detect
Zinc	Not Detected	5%	Non-magnetic; not inductively reactive

Each material was tested 50 times to ensure repeatability. The researchers achieved that ferromagnetic metals such as steel and iron can be recognized at 100% accuracy, but the response to non-ferrous metals such as copper and aluminium remains restricted; therefore, it is important to note here the difficulty in using the inductive sensor to identify those materials.

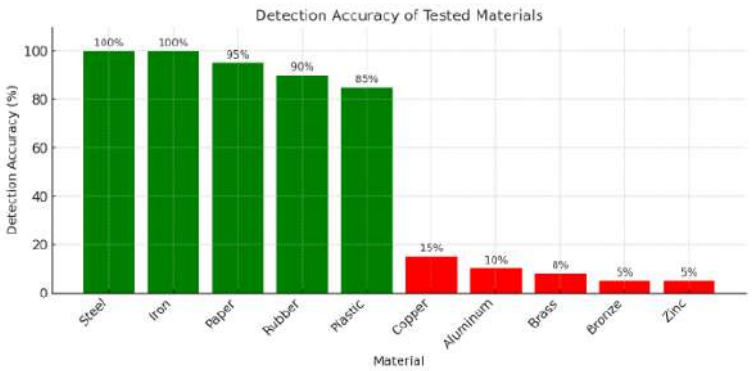

Fig. 3. Bar graph representing detection accuracy for each tested material

As is evident from Table II, our system is compared with other models of waste segregation employing diverse technologies [1]– [3], [6]. Of significance is that, while using simpler hardware, our architecture can produce competitive results, thereby demonstrating both its efficacy and relevance to real-world environments.

Table II. Comparison of our project's detection accuracy with previous research models

Model / Paper	**Materials Covered**	**Detection Accuracy (%)**	**Year**
Our Project	10	92	2025
SmartBin: IoT Segregator [1]	10	89	2022
SensorFusionSort v2.0 [3]	18	93	2023
WasteDetect AI Vision [2]	25	96	2024

The Fig.4 show its process of separating waste into metals and non-metals

Fig. 4. Steel being sorted into the metal bin

To create a proper background of our work, we have drawn insights from several recent studies on automated waste segregation systems [6], [8]. Most of these studies used technologies, including computer vision, machine learning, and IoT-based sensing. The

proposed system has been compared with the previous works in Table III below in terms of methodology, cost, energy, and detection.

Table III. Comparative analysis of existing waste segregation systems and the proposed model

Model / Paper	**Technology Used**	**Sensors / Hardware**	**Power Consumption**	**Cost**	**Detection Accuracy (%)**	**Advantages**	**Limitations**
SmartBin: IoT Segregator [1]	IoT + ML	Camera, Ultrasonic	High	High	89	Accurate for mixed waste	Requires cloud connection
WasteDetect AI Vision [2]	Deep Learning (CNN)	Camera (OpenCV)	Very High	Very High	96	Identifies 25+ categories	Expensive, not energy-efficient
SensorFusionSort v2.0 [3]	Sensor Fusion	Ultrasonic + Capacitive	Moderate	Moderate	93	Simple hardware	Requires calibration
Automated Conveyor Sorter [6]	Sensors + Conveyor	IR + Inductive	Moderate	High	90	Continuous operation	Bulky setup
Our System (Scrap Wise)	**Sensor Fusion (Ultrasonic + Inductive)**	**Arduino-based**	**Low**	**Low**	**92**	**Compact, low cost, portable**	**Limited to two classes (metal/non-metal)**

Based on Table III, it can be seen that the majority of previous works reach high accuracy by using methods that are computationally burdensome, such as at the level of deep learning or by processing through the IoT cloud, leading to a high-costs and power demand. In contrast, our system performs at competitive detection performance 92% with minimal sensors setup, providing a compromise among cost, power consumption, and reliance, making it practical for localized waste management utilization

3.2 Discussion

The findings from the project show that the use of advanced technologies in waste sorting greatly diminishes the workload of sanitary workers, freeing them from the mental stress and labor-intensive task of handling. However, this innovative system has a few limitations. It faces challenges, including the inability to handle excessive amounts or mixtures of materials, and it has been observed that these issues also affect similar low-cost IoT-based sorting systems [2], which can slow down operation. Moreover, it is unable to pick up certain types of metals. Hence these constraints ultimately influence the accuracy of the whole sorting process.

3.3 Limitations

This system has an effective rate of 92% but several limitations also exist. That's because testing was conducted with clean, tagged objects, and it may fail to work well identifying mixed waste. Moreover, future development must focus on training the system to recognize and separate both clean and soiled materials [7]. Similarly, if it relies on a 12V power source, a fixed electrical socket is required, which restricts mobility. Additionally, it has been found that the inductive proximity sensor will only detect certain metals. That restricts its ability to identify wide mix of metals commonly encountered in waste streams. These areas still need improvements.

3.4 Future work

Future additions to the system would include upgrading the technical aspects, including:

1. replacing the inductive proximity sensor for a more practical metal detector [4], such as general-purpose metal detectors, would greatly expand the scope of detectable metals. Since, as pointed out in an earlier review of sensors of this nature, it can pick up a wider range of metals.

2. Another way to achieve greater flexibility and sustainability is to use solar panels to replace the 12V power supply.

3. Expanding from two bins to three distinct categories, metal, wet, and dry, will enhance sorting efficiency. The above modifications are aimed at creating a stronger and more efficient waste division system that resembles real-world applications.

4. CONCLUSION

The proposed research verified the sensor-fusion model's feasibility of advanced indicator metal vs. non-metal segregation at a minimal expense. The described devices of ultrasonic and inductive sensors achieved up to 92% accuracy, proving that elementary and low-cost machinery can challenge special-purpose devices in terms of efficiency. Furthermore, our initiative contributes to these services by helping protect hygienic workers' health by reducing their contact with hazardous materials, as supported by previous studies on AI-based sanitation support systems. However, improvements are still needed to enhance the accuracy and adoption of our project. This would ultimately help sanitary workers in their tasks. Overall, this prototype demonstrates that low-cost, sensor-fusion systems can provide reliable and scalable solutions for waste segregation in resource-constrained environments.

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A Cost-Effective Smart Door Locking System to Support Disabled Individuals

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Abstract—A common challenge for individuals when faced with sudden mobility-related impairments caused due to injury, surgery or other medical conditions is the difficulty in performing simple everyday actions; Among these actions is opening and closing doors. This problem significantly affects the individuals who are in wheelchairs or wearing crutches. While automated door systems offer a convenient solution and are commonly available, installation throughout the household is not practical due to its high cost and complex assembly. This study demonstrates the working principle and methodology of a device developed to serve as a cost-effective alternative solution to this problem by prioritizing accessibility and flexibility. The proposed device also aims to support individuals who are temporarily immobilized with its design, focusing on simplicity as well as adaptability, which allows the user to install these devices without making permanent changes to their environment. Hence, this solution offers a cost-effective, practical solution that enables independence for these individuals.

Keywords— Elderly and Disabled, Home Automation, IOT, Smart Door

1. INTRODUCTION

Typically, in most households and public environments, Conventional door systems are not designed to accommodate individuals with limited mobility. Consider a scenario where an individual who has no physical disabilities unfortunately gets temporarily immobilized. This may happen due to an accident, and as a result, this individual is now required to be in a wheelchair for several months. Simple everyday tasks such as opening and closing doors have now become difficult and challenging. A typical solution for this is to install a smart door system, but most existing door systems are not affordable. This essentially shows that there's a need for devices that provide a quick solution; a solution that restores independence to individuals who are facing these sorts of challenges whilst being budget-friendly [1], [2].

This research introduces a new Smart Door Locking System that is designed to accommodate these exact needs. The device offers us three primary control modes: Wi-Fi for integration with smartphones and IoT systems, Bluetooth-based remote controls for quick access, and a manual control option for failsafe operation [3], [4]. When the system is initialized, the user can configure the device in several ways depending on what type of door the device is installed on. Its locking mechanism is built for easy installation, requiring only minimal use of tools, and it does not require making any modifications to the doors and structures. This advantage in design makes the system ideal for rental spaces and temporary care facilities.

Key advantages of this system include easy assembly, cost-effectiveness, and versatility. Unlike conventional smart door lock systems, which require complex setups, this proposed system requires a very minimal calibration and installation time. The Smart Door Locking System is designed to have the potential to be installed in various settings, such as residential areas, hospitals, and public facilities, and its security settings can be calibrated to meet the user's needs. Through this research, we aim to highlight the importance of adaptable design, and we will be discussing the working principles and methodologies of this proposed system.

2. LITERATURE REVIEW

Most modern automated smart door lock systems (or Handicap door lock systems) available online are driven by a top-mounted motorized arm mechanism for opening/closing doors. This design comes with high price margins ranging from around $149 and above. This proposed system utilizes a different mechanism to drive the door. The device is mounted at the bottom of the door instead of the top and is driven by a retractable wheel system. This efficient design results in a high-cost reduction, making the system more affordable for the user, especially when they are temporarily immobilized. The expected price range for this system is approximately $30 per unit and can be marketed in pharmacies and other medical outlets.

3. METHODOLOGY

The device is constructed to be easily installed at the base of virtually any door. It features a rotating wheel for opening and closing and uses a solenoid lock for locking and unlocking [1]. The wheel is connected to a gearbox that allows it to shift to neutral for free rotation during idle conditions. The wheel can also remain in a locked position, allowing the door to stay open at precise angles relative to its adjacent wall. A Proximity sensor is used to determine the distance of the door relative to the wall. The speed, timing of the solenoid, and live angular position are all dependent on these sensory inputs. The proximity sensor should be placed near the hinge of the door and should be oriented towards the annexing wall. Therefore, when the door opens/closes, the distance between the sensor and the wall varies; these changes in distance can be converted to angles using simple data mapping techniques [4], [5].

3.1 The Algorithm

When initializing the system, the user must connect to the device via a dedicated app. Here, the user can provide the Wi-Fi SSID and Password for internet connectivity. After establishing a connection with the device, the user must configure the device's security features. For modes like "Public configuration", where the device is placed in a public setting (e.g. public washrooms, halls etc.), the security features are relatively low as the device must be accessible by anyone in the public area. If the device is placed in a door that requires a higher level of security, the user can configure the device to "Private Configuration" mode. This mode features more security, such as password authentication for entry (via a dedicated app) and authorized Bluetooth remotes [3].

Once the device is configured, it must be calibrated. This can be done by opening and closing the door a few times and adjusting the sensor's position for optimal positional

feedback. Once the sensor is adjusted and the system is fully calibrated, the device can be turned off from calibration mode and it will work under nominal operation. When operating normally, the system stays idle until something triggers it. The triggering can be done either manually or by Wi-Fi via the app or using a dedicated Bluetooth remote.

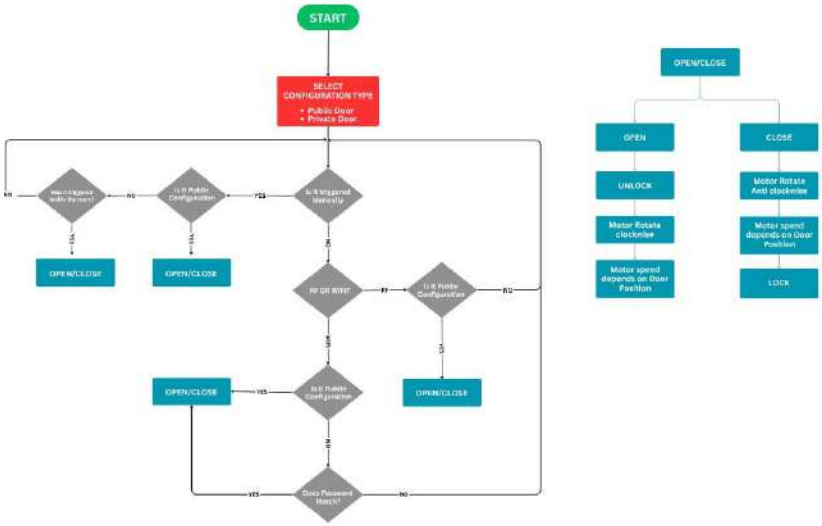

Fig. 1. Flow chart of the algorithm

After the system receives a trigger, it will make its next decision based on which mode it was configured. Say, if it was triggered manually from outside a room, then it would check if the configuration is private or public. For this scenario, if the configuration was set to public, the door would open. In the case of using the app, if the device is configured to be in a private configuration, the system will require a password or fingerprint authentication to open the door. If it's set to public configuration, the app will show the nearby devices and the user can select the device (or in this case, door) and open/close it. Permission for locking and unlocking the public doors can be configured in the app as well. When using the Bluetooth remotes, if the device is configured to be in private configuration, only registered remotes have access to open the door. Registration of the Bluetooth remotes can be done when the device is in calibration mode via the app. For the case of public configuration, the door will respond to any of the dedicated Bluetooth remotes within a certain proximity. Note that all the remotes are mountable on wheelchairs for better accessibility.

Apart from the main functions, several additional features are available. In the private configuration, features include Do not disturb: Users from the outside cannot access the door temporarily unless Do Not Disturb is off, Custom Door Position and Locking: The user can open the door in custom angles from 0-90 degrees (Note that the device has an error margin of 10-20 degrees). This position can be locked as well. Another great feature is the device's ability to make the door open/close freely like a normal door; this is especially useful for public areas where people without limited abilities can easily use

the door without any controller, but it will still operate for people with limited abilities when triggered.

3.2 System Design

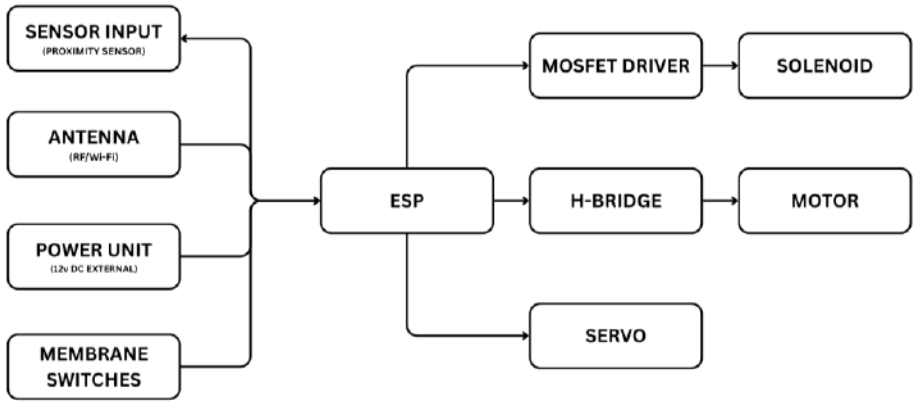

Fig. 2. System Design

The system consists of multiple peripherals each being connected to the main PCB. All these peripherals will be controlled and monitored using an integrated ESP32-C3 module. The module consists of its own built-in antenna, which the system will use for Wi-Fi communications. In this section, we will discuss the role of each unit in detail and how it will be connected to the main PCB.

3.2.1 Power Unit

The system will be powered by a DC12V 2A external Switch Mode Power Supply (SMPS). This approach has several key advantages, such as proper system isolation from main supply (AC 230v) and a stable regulated DC output with minimum ripple. The device's power is sourced from a standard DC barrel jack; this ensures modularity and simplifies maintenance, as the power supply unit can be readily replaced or upgraded without requiring any additional modifications to the system architecture [6].

3.2.2 Sensor Input

An Infrared (IR) based proximity sensor is used to determine the angular position of the door. The sensor will be mounted close to the door's hinge. When the door opens/closes, the distance between the sensor and the annexing wall varies. This distance variation is mapped to corresponding angular displacement values using linear interpolation or simple data mapping techniques. By continuously monitoring the position of the door, the ESP microcontroller can precisely control the motors' rotation just enough for it to open and close, ensuring accurate actuation with high efficiency. Additionally, the sensor's positional feedback is vital for user-defined door positioning, which can be performed via the app.

3.2.3 Membrane Switches

An array of membrane switches is positioned inside and outside of the door base. This allows the user to conveniently open/close the door from either side using their leg, offering a hands-free, ergonomic experience. Additionally, that the switches located on the outside can be disabled when the door is set to private configuration. This means the door can only be controlled via the app or the dedicated Bluetooth transmitters, which ensures that only authorized devices can operate the door.

3.2.4 ESP Module

The microcontroller used to control the entire system is an ESP32-C3 module, which supports 20-40MHz bandwidth in the 2.4GHz band and features Bluetooth 5 with speeds of up to 2MBps. The ESP module is directly mounted to the PCB instead of being embedded. This approach is more cost-effective and reliable as the ESP is optimized for the best performance [7], [8]. For cloud communication, protocols such as TLS 1.2+ will be used to ensure data confidentiality, integrity, and authentication.

3.2.5 Servo Motor

A low-power servo motor is positioned adjacent to the gearbox of the device, allowing it to change the wheel's engagement with the ground. Under nominal (idle) conditions, the wheel is always disengaged from the ground, which ensures the door moves freely and remains unobstructed when fully open. However, when the door is being commanded to open/close, the servo activates and pushes the wheel downward to establish contact with the floor. The servo's downward actuation also helps maintain consistent contact between the wheel and the floor surface, ensuring reliable traction even when the floor is uneven or irregular.

3.2.6 H-Bridge

To control the motor's rotation, a L298N motor driver IC is utilized. This IC is a low-power dual H-bridge motor driver specifically designed to rotate DC motors in both directions and can be used to make rotations for short periods. The motor driver IC also has a Pulse Width Modulation (PWM) control feature, which allows the ESP to precisely control the motor speed by changing the duty cycle of the input signal. This allows the device to have regulated acceleration and deceleration when the door starts to open or close.

3.2.7 Motor

The motor responsible for rotating the wheel, which opens and closes the door, is a standard DC 6-12V 100RPM Worm Gear motor. These motors are both cost-effective and efficient, delivering high torque with very minimal power consumption. The Gear motor will be connected to a separate gearbox with a 1:2 ratio to compensate for the slow speed. Additionally, this gearbox is designed to disengage the wheel from the floor until the servo motor is activated.

3.2.8 Solenoid and MOSFET Driver

The solenoid lock that is responsible for locking and unlocking the door is a universal car door lock actuator. These actuators are highly reliable, cost-effective, and can deliver

a significant force very efficiently. To drive this actuator, a MOSFET driver is used. The driver is based on an IRF540N N-type MOSFET, which can handle a drain-source current of up to 33A.

3.2.9 Power-Backup

In case of a power outage, the device can be operated for a short period of time using the device's built-in rechargeable Li-ion battery pack. During this time, the device's sensors and other peripherals will be turned off to conserve power. Only the locking mechanism and CPU will operate with full functionality. In the event of the batteries fully depleting, if the device is set to private configuration, the door will remain locked. This allows users from inside the room to manually open the door when necessary. If set to public configuration, the device will turn off, allowing users to enter and exit a room much like a regular door.

3.3 Schematic Design

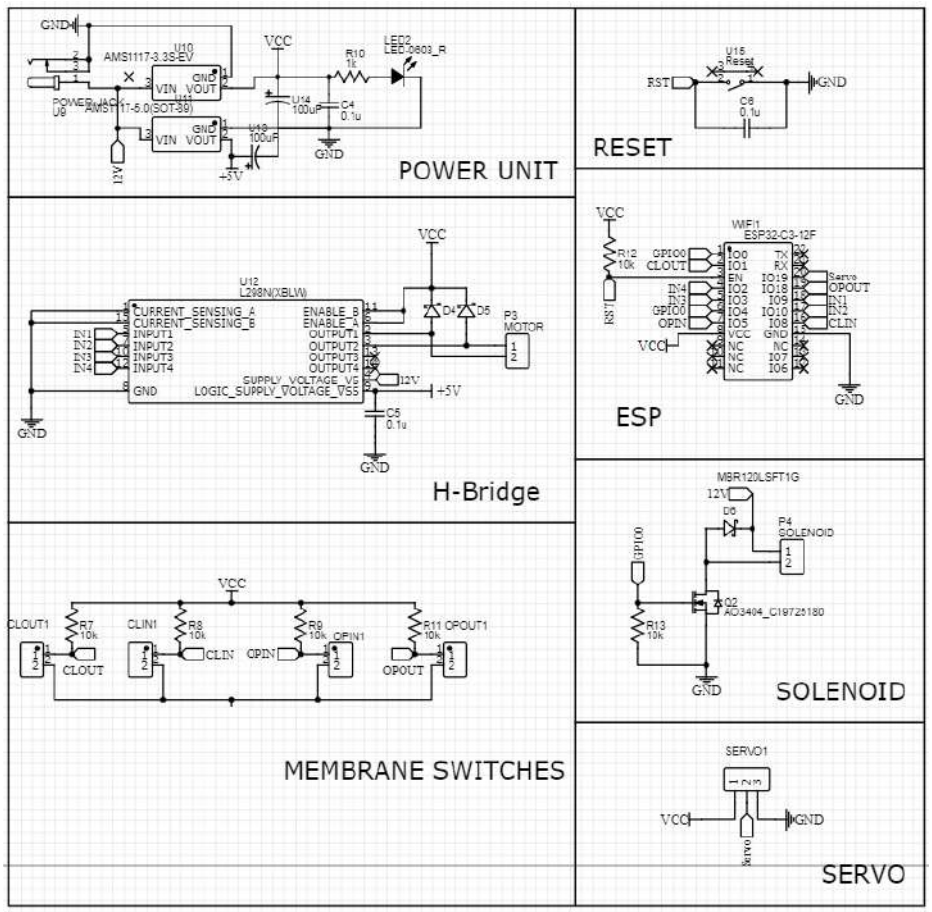

Fig. 3. Schematic design

The above circuit (Fig. 3.) is partitioned according to distinct functional sections. This makes analysis and understanding the circuit's operation easier. In the following discussion, we will be exploring each partitioned circuit and its functions.

3.3.1 Power Unit

As mentioned previously, the system's power is sourced from an external 12V DC 2A switched-mode power supply. This power supply is then connected to the device via a barrel jack in the PCB. The microcontroller used here (ESP32-C3) requires a constant 3.3V voltage input, and therefore an AMS1117-3.3 linear voltage regulator is used. Additionally, the L298N motor driver requires a logic supply voltage of 5V. This can be sourced from the 12V input via an AMS 1117-5, which is a 5V linear voltage regulator. These regulated outputs are then smoothened by placing decoupling capacitors of values 100uF and Bypass capacitors of values 0.1uF to suppress high-frequency noises to ground. Other pins, such as GPIO5, GPIO4, GPIO14, and GPIO13, are used as inputs, these will be connected to the membrane switches. GPIO2 also includes PWM capabilities and, therefore is used to control the speed of the motor.

3.3.2 Microcontroller

The ESP32-C3 is directly mounted to the PCB; this ensures cost-effectiveness, less complexity in the PCB, and efficiency due to its design optimization from the manufacturer. A reset circuit for the ESP is built into the PCB for debugging purposes. It consists of a switch that is pulled high and a capacitor to manage debouncing. The Pins GPIO9 and GPIO10 are used to control the direction of the motor. GPIO0 is used to control the Solenoid via a MOSFET driver circuit. Additionally, a diode is connected in reverse bias between the solenoid to prevent back EMF. Due to GPIO12 having PWM capabilities, it's been assigned to drive the servo motor that will engage and disengage the wheel from the floor.

3.3.3 H-Bridge

An L298N dual H-Bridge IC is used as the motor driver IC in this circuit. Its robust design, low cost, and high current handling capacity make it an ideal choice for driving the motor [9]. In the case of this device, only one section of the IC (section A) is used. Pins INPUT1 and INPUT2 are connected to the microcontroller to receive the directional input signals. ENABLE_A pin is responsible for the speed regulation of the motor, for maximum speed, the pin should be pulled to 5V. However, in our case, the ENABLE_A pin is connected to a PWM pin (GPIO2), which modulates the overall voltage by changing the duty cycle of the signal. Diodes D1 and D2 are included to minimize back EMF generated by the motor. Additionally, a 5V supply is fed to the LOGIC SUPPLY VOLTAGE pin, and a 0.1uF high-frequency bypass capacitor is placed between the LOGIC SUPPLY VOLTAGE pin to prevent large voltage spikes from entering the IC.

3.3.4 Membrane Switches

These switches are placed on the exterior of the device, facing both inside and outside of the room, enabling the user to manually open/close the door from both sides. The switches are located at the base of the door, allowing the user to control the device with

a simple kick. This ergonomic design concept helps users to conveniently control the door without needing to use their hands. Two main switches, OPEN and CLOSE, are placed on either side of the door. Additionally, the switches placed outside the room can be disabled for improved security. This can be configured via the app. The switches are internally connected to the PCB via JST cables, which ensure a secure connection even in the presence of vibrations.

3.4 PCB Design

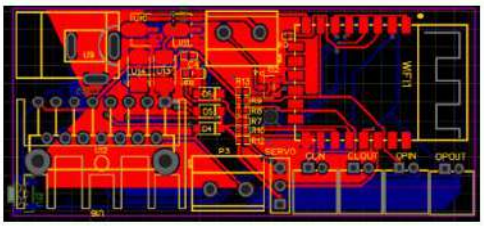

Fig. 4.1. PCB Layout

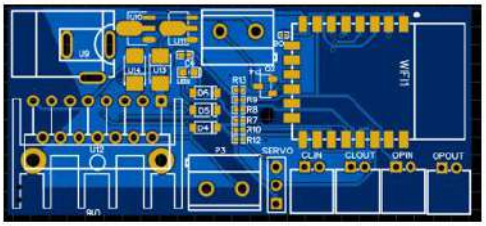

Fig. 4.2. Top View 2D

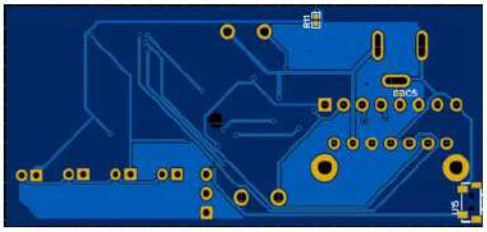

Fig. 4.3. Bottom View 2D

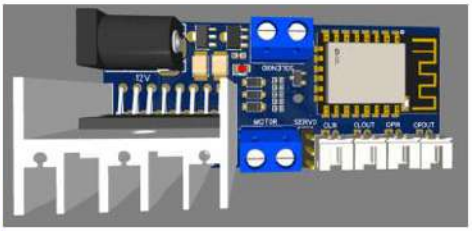

Fig. 4.4. Top View 3D

The PCB will be a two-layered board constructed using high quality FR-4 material, and it will also be of a 2mm thickness. This added thickness contributes to the PCB's mechanical durability and enhances its thermal performance by improving heat dissipation across layers. All peripheral components, such as switches and sensors, will be interfaced with the PCB through JST cables, which offer secure connections even with vibration from the door's movement. The motors and solenoids will be connected via screw-type Terminal blocks; this allows us to connect wires of a thicker gauge for better current handling, reduction of resistive losses, and ensuring better power delivery.

A heat sink is mounted on the L298N motor driver IC to manage the heat dissipation generated by the motor driver. The servo motor is connected to the PCB via a standard 3-pin male pin header. To ensure proper PWM connection to the servo without any interference, its connector is positioned near its respective GPIO pin. Additionally, a large ground copper area is located at the bottom of the PCB to minimize electrostatic discharges (ESD) and improve overall electrical grounding. Decoupling capacitors are strategically placed near the linear voltage regulators for immediate ripple suppression, and bypass capacitors are placed right after it to filter out any high-frequency noise and protect sensitive components from transient voltage spikes [10].

3.5 Gear Box Working Principle

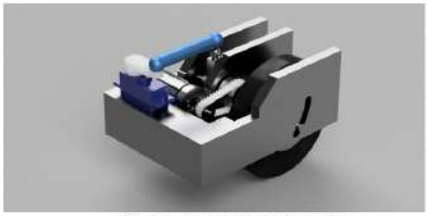

Fig. 5.1. Angled view of Gear Box

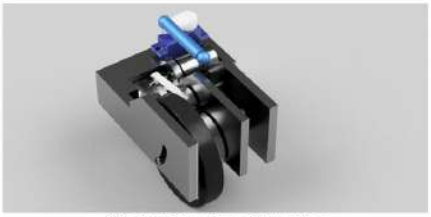

Fig. 5.2. Front view of Gear Box

Fig. 5.3. Front view of Gear Box

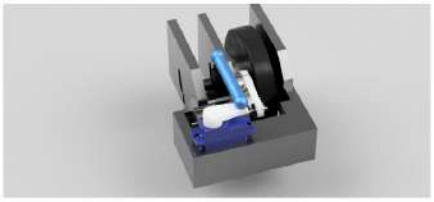

Fig. 5.4. Back view of Gear Box

The gearbox used here is encased in lightweight aluminum housing, which provides high structural integrity with minimal cost. This enclosure houses the DC motor as well as the servo motor, which is responsible for engaging the drive system. The wheel is mechanically linked to the gear motor in a 2:1 ratio via a toothed belt, ensuring efficient and slip-free power transmission. The wheel's contact with the floor can be engaged and disengaged using the servo motor's rotation. Under normal (idle) conditions, the wheel remains disengaged with the floor until the servo pulls it down and the motor is used. This ensures that the door behaves like a conventional door when it's open. This design not only provides functional efficiency, but it also works as a safety feature for situations where someone kicks the door by accident while it's open. If the wheel is disengaged, it won't cause any mechanical wear in the gearbox.

3.6 Mobile App Development

Fig. 6.1. Flowchart of the app UI

The above Figure 6.1 shows the flow diagram of the app's user interface. When the user logs in, they are brought to the home page, where they can either control a saved device, add a new device, or search for an existing device. After selecting the desired device, the user is presented with the available control features.

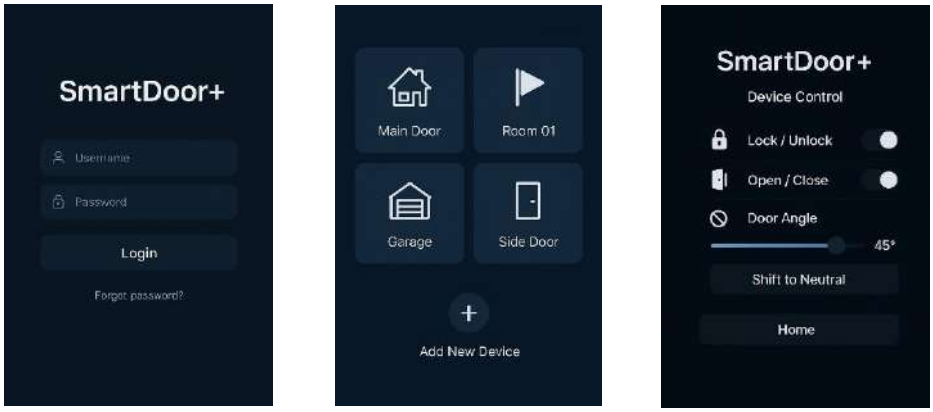

Fig. 6.2. Mobile App Preview

Fig. 6.2 shows a preview of the dedicated app used to control the system. A simple straightforward UI is used for quick access and simplicity. The app comes with features such as Do Not Disturb, Lock/Unlock and OPEN/CLOSE. Additionally, this same app can be further improved to be connected to other compatible home appliances, which in turn enables features like turning on/off room appliances when a person enters/exits [11]. When the user launches the app, they will be prompted to connect to the device. Once the device is connected successfully, a password can be set to the device if the device is used for private door configuration; this ensures restricted access and therefore increases security. If the device is intended to work as a public door, password protection is not required.

Within the app, users can access a range of configuration settings. Including adjustments for the door angle, opening/closing speed and sensor calibration for proper positional feedback. The app uses a real-time database provided by Google Firebase. This allows the user to connect to control the door remotely from any location worldwide. This cloud-based connection also helps the user get instantly notified whenever the door has been opened, offering added security and awareness when the user is away from home [12]. It's important to note that only devices that are configured under private mode have access to cloud-based control via the Firebase database. Devices that are intended for public use are limited to local control and can only be operated within the same Wi-Fi network range, ensuring security and preventing unauthorized remote access.

4. CONCLUSION

Although this device is intended to work as a temporary solution for individuals who suffer from mobility impairments, its utility is not restricted towards them only. Thanks to the device's ergonomic design, cost-effective hardware, and non-invasive installation, it serves as a practical enhancement for a wide range of users. The core of the system is powered by an ESP32-C3 and comes with Wi-Fi and Bluetooth connectivity and manual control features via membrane switches. This multi-modal control architecture allows users to interact with the door system both locally and remotely. The system is also capable of smart home integration, allowing it to interact with other compatible electrical devices, making it have features like toggling lights when the user enters or exits the room. The device has 2 main modes, private configuration and public configuration. The private configuration mode has added security, requiring password authentication for entry via the dedicated app or requiring a signal from assigned Bluetooth remotes. The public configuration mode does not require password security, and it can be operated manually or with any dedicated Bluetooth remote.

In terms of electrical design, the device is powered by an external DC 12V 2A power source, which provides additional isolation and protection from high voltage spikes and offers the convenience of easy replacement. Some future implementations include the addition of voice control capabilities for public mode access, Bluetooth connectivity for versatility, and further improvement of emergency power backup systems to ensure continued operation even during power outages.

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TECHNICAL SESSION 3

ENERGY, ELECTRICAL, AND POWER ENGINEERING

Analysis on Current and Power Variation with Voltage of PV Arrays Under Hybrid Partial Shading Conditions

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Abstract—Partial shading is a crucial challenge for solar power generation in photovoltaic systems, and it significantly impacts their reliability and performance. Previous research has explored partial shading effects using I-V and P-V characteristics under standard partial shading scenarios like uniform, row, column and diagonal patterns separately mostly focusing on small scale Photovoltaic (PV) arrays. Even though they successfully demonstrated how shading affects module performances and Maximum Power Point Tracking (MPPT), they overlook the complexity of real-world scenarios where multiple shadings can occur simultaneously. This study introduces a novel hybrid partial shading simulation model that integrates uneven combinations of row, column, and diagonal shading patterns to emulate real world and dynamic shading conditions. Furthermore, the model was effectively simulated on a large scale 50kW PV array under various partial shading conditions, including even and uneven, uneven hybrid and varying shading factors, using MATLAB/Simulink. The analysis is carried out with the support of I-V and P-V characteristics curves, which fall under the traditional electric class of PV fault detection and diagnosis. Hence, the detailed analysis of I-V and P-V curves under different partial shading conditions put forth a foundation for intelligent fault detection systems using AI models, and thus this method produces abundant fault data for machine learning models without requiring expensive experimental setups.

Keywords—Fault detection and analysis, I-V characteristics, partial shading, photovoltaic arrays

1. INTRODUCTION

Solar Photovoltaic (PV) systems have emerged as an essential source of the global transition to renewable energy, while offering scalable, environmentally friendly and sustainable solutions for global electricity demands. However, despite the rapid growth of PV installations worldwide, there is a significant gap that still exists between the required global energy demand and the actual generated energy from solar PV systems. Closing the gap is not only about ramping up solar deployment but also about improving efficiency, reliability, and fault tolerance of the installed base to perform at optimal levels under a broad array of environmental and operating conditions.

Solar PV systems are susceptible to various factors that can seriously affect their

operational performance, energy yield, and their lifespan and may cause damage to the system components and lead to dangerous fire hazards. Basically, PV system faults are classified into physical, environmental and electrical faults [1]. All these faults are under two basic fault types which are DC side faults and AC side faults. Faults in DC side are affecting the whole generation because, if the electronic devices of system cannot extract a large amount of power from the PV generators, then it will cause the whole PV application to become unsuccessful. Among them, partial shading is one of the primary and complex DC side faults which can be caused by trees, nearby buildings, poles or clouds that can lead to uneven irradiance across modules causing reduction of power generation, introducing current mismatches within series-connected modules.

Applying fault detection techniques is of two classes, non-electric class which includes visual and thermal methods or electrical based methods based on structured Electrical Measurements and environmental data such as IV characteristic curve analysis [2]. This IV characteristic curve analysis is a very powerful electrical method for detecting and diagnosing PV array faults on deviations in the current-voltage profile. Usually under normal conditions, a PV module's I-V curve gives a smooth knee at the maximum power point, but when a fault occurs due to partial shading this curve gets distorted. Since each type of fault causes distinct distortions on the I-V curve, technicians or algorithms can identify the fault thorough analysis of I-V curves. However, many of the studies have primarily focused on simple or uniform shading patterns for small-scale PV arrays, whereas this research introduces a hybrid partial shading model which combines multiple shading patterns on a large-scale PV array.

2. RELATED STUDEIS

I-V characteristics curve analysis for partial shading in PV arrays

Research has employed a range of methodologies to study and detect partial shading using I-V curve characteristics. Some of the methods include simulation modeling, controlled experimental measurements of I-V curves and advanced methods like applying machine learning to I-V data, due to its powerful as well as a flexible technique for diagnosing PV array faults. I-V characteristics curve analysis falls under traditional electric class of PV fault detection and diagnosis where the curve characteristics gives the short circuit current, open circuit voltage, fill factor and maximum power point (MPP) where each of these parameters responds characteristically to shading-induced mismatches. Due to non-uniform irradiances in partial shading across modules, current imbalances could be observed, and the bypass diode activates causing changes in standard I-V curve. It creates visible multiple Local Maximas (LMs) in the corresponding PV curve.

The study in [3] has analyzed the behavior of series connected silicon-based PV modules under partial shading using a validated one-diode model. Their results have shown that the shading leads to comparative mismatch losses, multiple MPPs and large shifts in MPP voltages often well below the expected 80% of open-circuit voltage. R. Ahmada et al. [4], used I-V curves to analytically study the effects of partial shading on PV arrays. They found that bypass diode activation causes local maxima to occur close to multiples of the

open-circuit voltage. Their approach, which doesn't require sophisticated tools, helps forecast fault patterns and maximize MPPT performance. In the study F. Salem and M. A. Awadallah [5], an ANN-based method for detecting and evaluating partial shading in PV arrays was presented. By examining I-V characteristics and output power variations, their model precisely calculated the shading factor and the number of shaded modules. A critical irradiance points below which the maximum power becomes almost insensitive to additional shading was found in Teo et al. [3] when they examined the effects of partial shading on PV strings. Using MATLAB/Simulink, they created and verified a mathematical model that demonstrated how the number of shaded modules and shading intensity affect the PV curve's peak transition and power drop behavior. Furthermore, the study by S. R. Pendem and S. Mikkili [6] used MATLAB/Simulink to model and simulate several PV array topologies under different partial shading patterns. They have assessed the results based on I-V and P-V characteristics. Their analysis demonstrated how the most robust configurations, such as the Total-Cross-Tied (TCT) topology, in reducing shading losses were identified through curve behavior, including multiple peaks, voltage drops, and mismatched currents.

3. METHODOLOGY

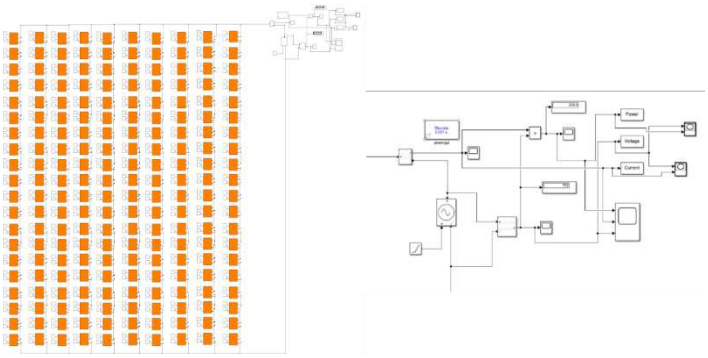

Fig. 6. 50kW PV array modelled using MATLAB/Simulink

In this study, a commercially available 50 kW solar photovoltaic plant, comprising 200 modules, was selected. This facility is situated at the Eastern University-Auditorium in Vantharamoolai, Sri Lanka. Utilizing pertinent calculations, along with data from the photovoltaic modules and inverters, the modules were organized into ten strings, each consisting of twenty modules. These data were used in MATLAB/Simulink software to virtually build the PV array system as in Fig 1 and conducted an analysis of the 50kW PV power plant's behavior under various faults and shading scenarios. Each PV module was parameterized using manufacturer datasheets which included standard test condition values for maximum power point characteristics, open circuit voltage and short circuit current.

To test the PV array performance, standard condition assumptions which are the cell temperature of 25°C and an irradiation of 1000 W/m^2 were given [6]. These settings were employed in simulation because they provide a consistent baseline for comparison against fault scenarios and benchmark performance. A bypass diode was also included

with each module to guard against overheating and possible damage in the case of mismatch or shade.

4. RESULTS AND DISCUSSION

Analysis and diagnosis of PV array performance under diverse partial shading conditions

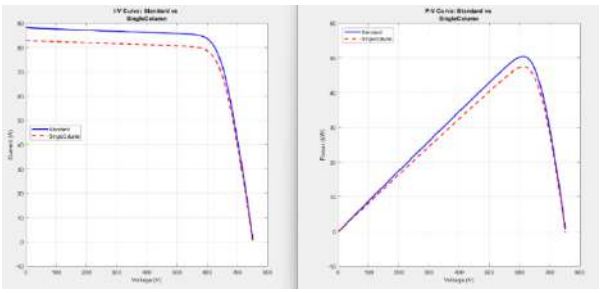

Fig. 2. I-V and P-V curves when a single column is shaded (1st string)

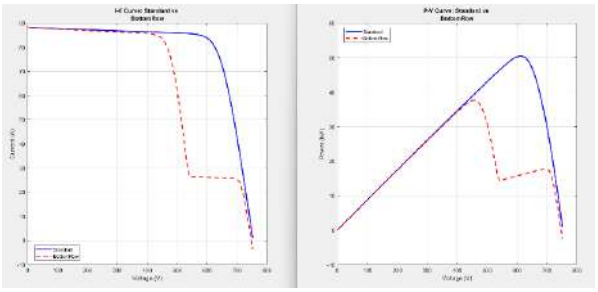

Fig. 3. I-V and P-V curves when a bottom row is shaded (1st string)

In this study, the analysis is carried out under three main categories: the first two categories are even and uneven shading patterns which exhibit consistent irradiation reduction across modules and a range of irregular irradiances on each module. The third category is partial shading characterized by shading factors. Particular attention is given to hybrid shading conditions of non-uniform shading patterns where we assume two types of shading scenarios happen at the same time which enables a deeper understanding of PV system response to complex and realistic shading environments.

Impact of even shading patterns

Case 1: Column shading (wall/tree shadow)

A string is under uniform shading configuration resulting in a consistent reduction in photocurrent generation. The I-V curve of Fig 2 depicts the current drop from no fault condition short circuit current. It causes the P-V curve to exhibit a lower peak, indicating

a reduction in power extraction.

Case 2: Row shading (wall/tree/billboard shadow)

A noticeable step in the I-V curve in Fig 3 signifies that the bypass diodes in each string's first modules have been activated, thereby bypassing the shaded modules while limiting the voltage contribution from each string. In the P-V curve Fig 3, this behavior translates to a noticeable reduction in maximum output power and the emergence of a local maximum, caused by mismatched conditions across strings.

Case 3: Central shading (A cloud, a tree canopy)

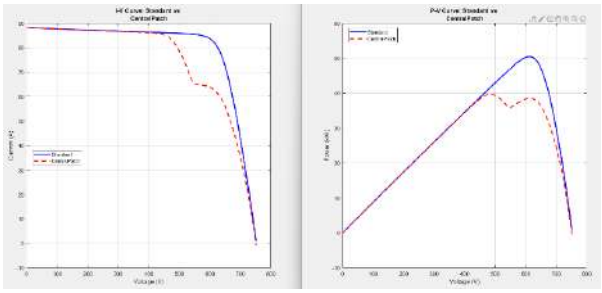

Fig. 4. I-V and P-V curves when several modules in middle are shaded

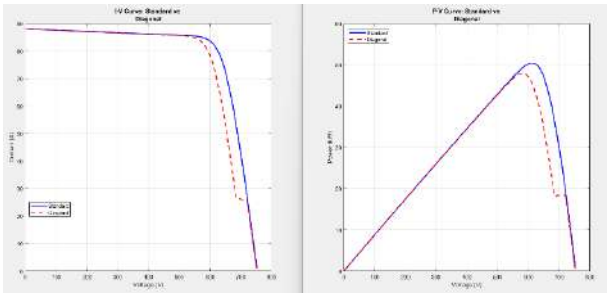

Fig. 5. I-V and P-V curves when diagonally shaded

As shown in Fig 4, the I-V curve exhibits multiple current steps, indicating the activation of bypass diodes in the centrally shaded modules. These steps are triggered as the shaded modules reach their current limit and are bypassed to maintain overall string current. Consequently, the P-V curve Fig 4 reveals multiple local maxima and a drop in peak output power compared to the standard case.

Case 5: Diagonal Shading (A building edge/pole shadow)

In this case, the diagonal shading across the PV array simulates realistic conditions like edge shadow of nearby buildings or pole. Modules were simulated to shade from one corner to the other corner diagonally with same irradiance value. The I-V curve in Fig 5

exhibited a gradual decline in current near the MPP and a smooth transition as bypass diodes across various strings activated at different voltages. Unlike uniform or row shading, the bypass events in diagonal shading are not synchronized across strings, leading to a more distributed and subtle inflection in the I–V curve rather than distinct steps.

Impact of uneven shading patterns

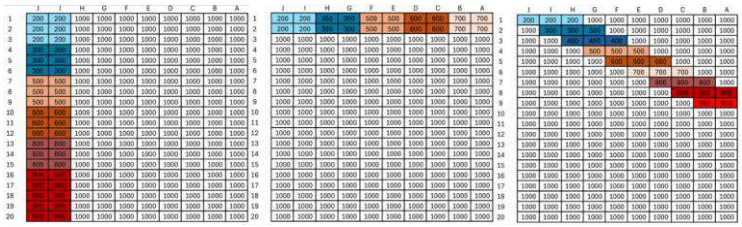

Fig. 6. Uneven column, uneven row, uneven diagonal shading

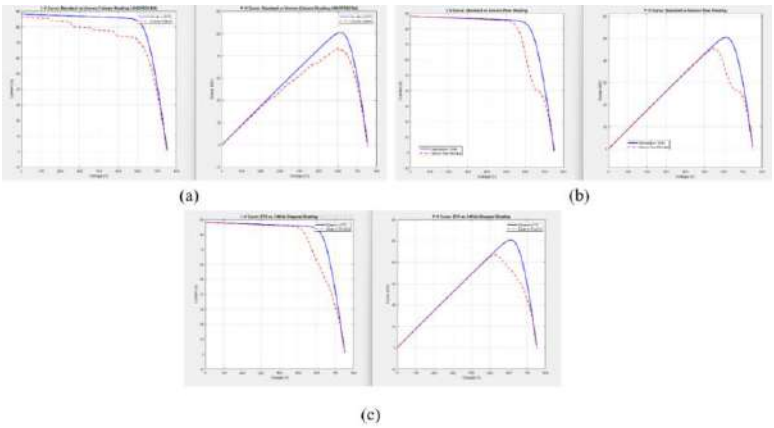

Fig. 7. I-V and P-V curves of (a) Uneven column, (b) Uneven row, (c) Uneven diagonal shading

The characteristics of the series-parallel photovoltaic (PV) array under the given shading conditions distinctly reflect the type and pattern of shading, enabling fault identification and classification. In case in Fig 6, uneven column shading (1st matrix), the I–V and P–V curves Fig 7 (a) shows a significant drop in current due to shaded two strings, especially past mid-voltage where shaded strings begin to drop out due to bypass diode activation leading to reduction in peak power. Fig 6 uneven row shading (2nd matrix), significant voltage drops before reaching its STC values in Fig 7 (b). In contrast, Fig 6, uneven diagonal shading (3rd matrix), shows more complex nonlinear characteristics Fig 7 (c), with irregular reductions in voltage and current across the array, producing multiple peaks and an irregular power-voltage curve. These distinct signatures can be effectively used to identify shading patterns through advanced algorithms or artificial intelligence

techniques, thus enhancing diagnostic accuracy and facilitating targeted fault mitigation.

The analysis continues hybrid shading patterns which is introduced in this study to better show how photovoltaic (PV) arrays are affected by real-world shading conditions that are both complex and dynamic. Hybrid patterns, on the other hand, combine different types of shading, like uneven row, column, and diagonal shading. This makes the array's electrical output change in more complex and realistic ways. These hybrid patterns are important because they make I–V and P–V curves that show multi-directional mismatches happening at the same time. These mismatches are often caused by things like buildings, poles, trees, or dirt building up. Studying these types of circumstances not only allows us to understand how arrays work more effectively but it also makes intelligent fault detection and classification algorithms more accurate and useful. This work contributes to developing PV monitoring systems that are more reliable and accurate by adding these combined scenarios.

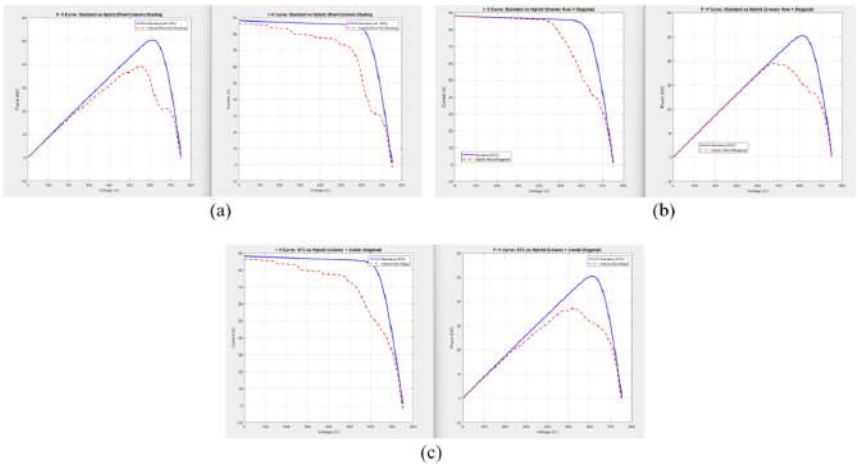

Fig. 8. Hybrid shading (a) uneven row and uneven column, (b) Uneven row and uneven diagonal, (c) Uneven column and uneven diagonal

5. CONCLUSION

Using MATLAB/Simulink which is a simulation-based analysis of a 50kW photovoltaic (PV) array under various partial shading conditions has demonstrated that partial shading significantly distorts the I–V and P–V characteristics curves under STC, affecting power output and making fault identification more challenging. This study has identified unique electrical signatures that can be used as trustworthy evidence of fault types by simulating various shading scenarios, such as uneven, hybrid, and graded shading intensities. These simulation results offer a scalable framework for producing labelled datasets that are necessary for AI-driven diagnostic models, in addition to an effective method for researching shading effects in large-scale PV systems.
The data acquired from these simulations will be used in future studies to create and train artificial intelligence models for automatic fault detection and classification, specifically neural networks and support vector machines. To improve reliability, lower

maintenance costs, and support predictive maintenance strategies in smart energy infrastructure, this approach seeks to develop intelligent PV monitoring systems that can detect faults in real-time.

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Harvesting Mechanical Energy from Tree Movement for Usable Electrical Power

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Abstract— This research explores a novel method of mechanical energy harvesting from ambient tree sway and its conversion to beneficial electrical energy using low-cost electromechanical devices. The study is motivated by the need for renewable micro-energy harvesting in canopy-covered or off-grid areas, where conventional solar and wind systems are not viable. Two energy conversion mechanisms were proposed and tested: a rotational generator system with a pulley-gear transmission system connected to a DC generator, and a linear generator system through magnet–coil interaction. Both systems were implemented, simulated in MATLAB/Simulink, and experimentally tested under controlled and outdoor conditions. The rotational generator reached a peak of 324 mV and produced a peak-to-peak output of 536 mV, which was a far greater performance than that of the linear generator, whose peak voltage was 6.08 mV. The result of the experiment demonstrated that mechanical amplification using gearing mechanisms is more effective under low-displacement motion conditions typical of tree sway. The study confirms the viability of exploiting natural tree movement as a renewable micro-power supply for powering low-power devices such as environmental sensors or LED lighting in remote areas. The findings contribute to advancing sustainable energy harvesting technology and open new possibilities for the implementation of motion-powered systems in Sri Lankan forested and semi-urban environments.

Keywords—Tree sway energy harvesting, rotational generator, linear generator, micro-energy systems, renewable energy, mechanical-to-electrical conversion

I. INTRODUCTION

The global transition towards renewable and self-renewable energy sources has spawned a resurgence of research in alternative sources of energy harvesting, particularly in decentralized, off-grid, and environmentally sensitive areas. Traditional renewable systems like solar panels and windmills are impractical or inefficient in most such areas, especially in forest canopies where dense trees cover obscures sunlight and air flow. However, there is a natural and under-exploited source of kinetic energy in such systems that is tree movement, stemming from wind-induced sway. The low-frequency periodic movement presents potential for micro-scale energy harvesting, especially when harvested and converted with mechanical-to-electrical energy systems.

Previous research has established that the swaying motion of trees, though low frequency and amplitude, has mechanical energy that could be harnessed by the right mechanisms. McGarry and Knight, in [1], showed the feasibility of using a cord-pulley system on a swaying tree to generate energy and power sensor nodes in forest

ecosystems. Their work identifies the possibility of tree movement as a source of energy that is sure to bear fruit in situations where there is no access to normal grid electricity or where solar and wind power are not viable due to environmental constraints.

Inspired by such approaches, this work explores a hybrid system to harness mechanical power from tree movement and convert it into usable electrical power. Two such systems are developed and tested:

- A cord, pulley, and gear set rotational generator system that is intended to amplify motion and drive a DC generator.
- A wound coil arrangement where magnets oscillate to induce voltage through electromagnetic induction.

This two-system approach is viable to facilitate comparative assessment between mechanical amplification by gear systems and direct magnetic coupling. The rotational system was more effective since it could translate small displacements into high rotational velocities using gear ratios, with the trade-off of increased voltage output. Nevertheless, the linear generator still exists as a low-complexity alternative with potential for improvement.

Sri Lanka itself offers a very apt environment for this research. The majority of the country's rural and semi-urban regions offer canopy-rich zones where solar panels or wind turbine installation is impossible. Yet, the ubiquitous availability of tree oscillation from monsoonal and routine wind patterns offers an opportunity to implement such power harvesting systems to provide energy for micro-load applications like LED streetlights, environmental sensors, or LoRa nodes with minimal environmental disruption.

Multiple past studies have also established the feasibility of the same mechanisms. For example, Living Plant-Hybrid Generals for Multidirectional Wind Energy Conversion established the use of hybrid systems that generate energy from the motion of the plant in different axes, further establishing the biomechanical approach of renewable energy [2]. Other studies, like [3], provide basic research on coil-wound linear generators and prototype development practices that are used directly in this project.

The application relevance of this work falls into three broad categories:

- Demonstration of feasibility: To show that tree sway as a feasible mechanical energy source with practical voltage outputs is possible.
- Validation of design: Designing scalable and affordable systems for application in the real world.
- Adaptation to renewables: Addressing the micro-power needs of canopy and forest spaces in Sri Lanka, facilitating the country's shift towards renewable energy infrastructure.

Following sections present the design process, experimental setups, and experimental results of both the generator systems along with discussion and recommendations for field demonstration. The intention behind this work is to prove the concept for scalable

tree-based energy harvesting systems that can be used for powering low-power devices in remote, natural, or resource-starved locations.

2. METHODOLOGY

This research employed a mixed-method experimental design of mechanical prototyping, simulation-based modeling, and oscilloscope-based data acquisition for designing and testing two distinct energy harvesting mechanisms based on tree sway: a rotational generator system and a linear generator system. These two systems were individually designed, fabricated, and tested under simulated and field-simulation environments to determine feasibility, efficiency, and practicability for applications in micro-energy applications such as powering sensors or lighting units.

2.1 Design Strategy and Rationale

The project began with research investigations in mechanical motion conversion mechanisms suitable to tree swaying motion low-frequency, low-amplitude, and non-periodic oscillations. Initially, the crank-rocker linkage concept was followed based on Huseyin Mutlu's work on closed-loop kinematic mechanisms for vibrational energy harvesters [4]. Due to its mechanical complexity and challenges in field installation, however, it was deemed impractical for real-tree installations. The study then transitioned to the use of rotational energy conversion with gears due to its advantages of angular velocity amplification and mechanical simplicity, also underscored in rotational harvesters designed in [3] and [5]. In parallel, also envisioned was a linear generator system borrowing concepts from marine and wind-harvesting systems that utilize vertical or horizontal magnet-coil motion to generate power [6] [7].

2.2 Rotational Generator Configuration

The prototype rotational generator used a small tree or flexible vertical rod to simulate tree motion. A string was tied around a branch and wired around a 3D-printed pulley (diameter: 2.5 cm), the other side having a counterweight. The pulley shaft was welded to a large gear, which turned into a smaller gear (gear ratio: 1:3). The meshed gear compounded the rotation and drove a DC micro-generator, producing measurable voltage when the tree moved and tightened the cord.

Key mechanical components were:

- Pulley: PLA 3D print
- Gear train: Plastic gears with 3:1 ratio
- Generator: Brushed DC motor (used in reversed mode)
- Oscilloscope: Used to record the waveform
- Load: 100g to 200g weight tuned by tree strength

This device was also trialed outside and then stabilized within the indoor setting to allow oscilloscope capture. Tree swaying was mimicked manually at significant frequencies (0.4–0.6 Hz) with displacement amplitudes of ~10 cm, following findings in existing work in [8].

2.3 Linear Generator System

Several linear generator prototypes were developed. Each consisted of a magnet-slider moving inside a coil-wrapped tube:

Prototype 1: N42 neodymium magnet slider and PVC tube, 300 turns of AWG 26

Prototype 2: Low gauge coil and multi-magnet array plastic tube

Prototype 3: Aluminum T-slot rail for guided movement (failed because of its weight)

Prototype 4: Lighter coil with additional turns and smaller wire (output slightly improved)

These experiments utilized configurations derived from [9] and marine linear generators explained in [6]. Irrespective of multiple iterations, the linear generator's output voltage was low (peak voltage: 6.08 mV), not high enough for standalone operation but viable when power conditioning circuits are coupled with it.

2.4 Data Collection and Analysis

- Instrumentation: The oscilloscope was connected across the generator terminals to examine real-time waveform characteristics.
- Parameters measured: Peak voltage, frequency, waveform symmetry, and peak-to-peak values.
- Results: Rotational generator provided ~324 mV peak voltage and ~536 mV peak-to-peak. Linear generator provided 6.08 mV peak and 5.52 mV peak-to-peak.

These parameters were used to determine energy harvesting capability under typical sway levels. Further MATLAB simulations replicated mechanical displacement and angular velocity transfer using ideal spring-damper system models to validate theoretical performance, though results were not the main metric of measure utilized in this research.

2.5 Method Evaluation and Challenges

The rotating system was more efficient due to:

- Force transmission directly through the cord-pulley-gear assembly
- Improved rotational speed suitable for DC motor generators
- Consistent and uncomplicated components

The linear system, although theoretically promising and environmentally friendly (as discussed in [2]), also suffered from the following issues,

- Low magnetic flux linkage
- Friction of slide mechanism
- Winding restrictions and enormous structural design

But both systems validated the concept that swaying trees can generate useable electrical power, and they endorse the growing body of research on micro-energy harvesting from biomechanical sources.

3. RESULTS AND DISCUSSION

Experimental verification of the proposed energy harvesting device was achieved by analyzing the electrical output of two different setups: a rotational generator and a linear generator, both driven by simulated tree sway motion. The central aim was to assess the efficiency of energy conversion from small-scale biomechanical tree movement into usable and quantifiable electrical energy suitable for micro-power use.

3.1 Linear Generator Performance

The prototype linear generator was built using a copper-wound solenoid and sliding neodymium magnet core to simulate vertical oscillation caused by tree movement. The prototype oscilloscope values (see *Fig. 1* and *Fig. 2*) indicated peak-to-peak voltage of 5.52 mV and amplitude of a maximum 6.08 mV. Despite the relatively low output amplitude, the waveform clearly demonstrated that there are detectable voltage spikes representing the motion of the magnet through the windings of the coil. The sharp, spiky waveform trace (as seen in *Fig. 2*) represents transient effects related to drastic changes in magnetic flux, in agreement with Faraday's Law of Induction, on which the mode of operation of the linear generator is founded:

$$\varepsilon = -N\frac{d\varphi}{dt}$$

Where:

- ε is the induced EMF (voltage),
- N is the number of turns in the coil,
- φ is the magnetic flux.

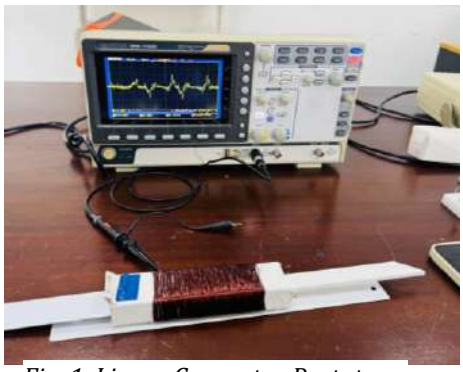

Fig. 1. Linear Generator Prototype

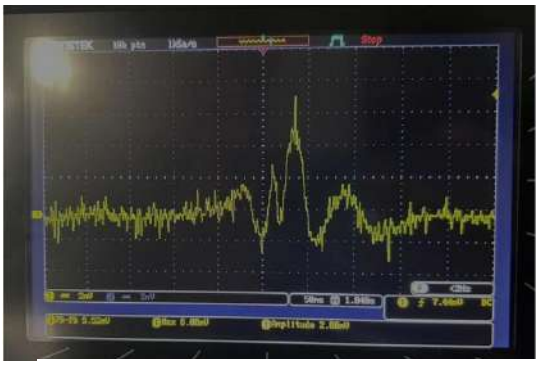

Fig. 2. Linear Generator Oscilloscope Results

The relatively low output is a result of limited relative velocity, limited stroke length of the magnet, and coil impedance and alignment tolerance losses. Waveform amplitude

also changed significantly with the frequency and force of oscillations, which were simulated manually from measured tree sway emulation of natural hand movement.

3.2 Rotational Generator Performance

The proof-of-concept rotational generator incorporated a pulley and gear system to amplify motion and rotate a small DC generator and had significantly higher performance in voltage output. Oscilloscope measurements (*Fig. 3*) have peak-to-peak voltages of up to 536 mV and highest instantaneous voltages of 324 mV, under optimal motion.

Additionally, periodicity of the waveform was in accordance with the simulated frequency of sway of about 0.5–1 Hz that is the same as that observed in actual tree movements in low-wind velocities. The experimental data confirms the mechanical gearing approach used in this system. Mechanical speed gain in terms of angular speed by virtue of the pulley-to-gear ratio greatly increased the output even with low initial input movement.

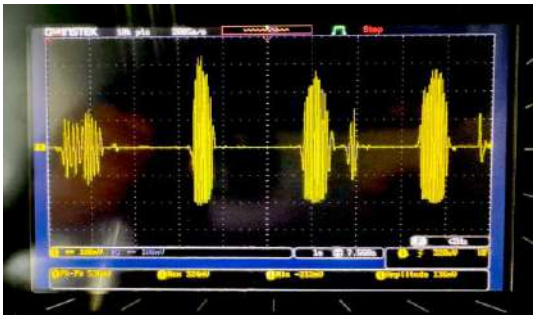

Fig. 3. Rotational Generator Oscilloscope Results

Fig. 4. Rotational Generator setup: Indoor Experiment

Fig. 5. Rotational Generator: Outdoor setup

3.3 Comparative Analysis

TABLE 1 Comparative analysis of linear and rotational generators

Parameter	Linear Generator	Rotational Gnerator
Max. Voltage output (Vmax)	6.08 mV	324 mV
Peak-to-Peak Voltage (Vpp)	5.52 mV	536mV
Wave form Type	Transient Spikes	Sinusoidal + Stable Peaks
Output stability	Low	High
Mechanical complexity	Low	Moderate
Feasibility in Harsh conditions	High	Moderate

As is apparent from the comparison, while the linear generator is less complex and possibly more durable (having fewer moving components), its electrical output is severely restricted without huge motion or optimization. By contrast, the rotational generator has the ability to produce up to 50 times the amount of output voltage and thus is the choice to be used for applications where substantial motion amplitude can be provided.

But observe that the rotational system is subject to mechanical wear-and-tear problems, namely at points of connection like the pulley bearings and gear interface. This compromise between reliability and output performance is necessary for application to remote or canopy-covered areas of Sri Lanka where maintenance access is limited.

3.4 Real-World Significance and Implications

These results indicate that natural tree motion commonly untapped biomechanical movement can be transformed into micro-scale electrical power, sufficient for LED markers, wireless sensor nodes, or ecological monitoring systems. In Sri Lanka's Forest and canopy-covered regions where solar exposure and wind exposure are restricted, this technique offers an available alternative to localized renewable energy harvesting.

Moreover, capacitor-based storage integration, ultra-low-power microcontrollers, or boost converters can further increase the usability of the harvested energy. As a first proof-of-concept, measurement of the waveforms ascertains theoretical modeling and opens up avenues for future research involving energy storage, power conditioning, and adaptive harvesting systems.

4. CONCLUSION

The research successfully demonstrated the ability to harvest mechanical energy from natural oscillation of trees and convert it into usable electrical energy through rotational and linear generator mechanisms. The experiments confirmed that minor, low-frequency motions typical of trees can generate measurable electromotive force (EMF),

as theorized based on Faraday's Law of Electromagnetic Induction. Of the two systems that were evaluated, the rotational generator, which employed a pulley-driven gear set and a DC generator, provided superior results with peak instantaneous voltage at 324 mV and peak-to-peak voltage of 536 mV with stable waveform consistency and replicable performance under indoor and field testing. In contrast, the linear generator produced relatively lower output of a maximum of 6.08 mV, constrained by magnetic flux, coupling misalignment, and slow oscillation speed.

These findings show that mechanical amplification in gear systems provides a more efficient means of biomechanical motion to electrical energy transformation compared to direct magnet–coil translation in the low-displacement context. The findings validate the laboratory feasibility of tree mobility as a renewable micro-energy source, particularly for off-grid dense canopy areas where solar and wind systems are constrained. The rotational concept system can be optimized and scaled to supply low-power devices such as wireless sensor nodes, microcontrollers, and LED lighting systems for facilitating distributed Internet of Things (IoT) applications for environmental monitoring and smart forestry.

Aside from showing the principle experimentally, the work also lays the ground for simulation-based optimization. Simulation of voltage waveform characteristics as observed experimentally was provided by the MATLAB/Simulink model to validate assumptions of mechanical-to-electric conversion. Optimizations of the generator design using multi-stage gearing, magnetic flux concentrators, and energy storage circuits that optimized will be done in future work. Hybrid models based on tree sway and piezoelectric or wind-assisted inputs will also be studied.

In the process, this work supports the broader goal of sustainable micro-energy solutions by transforming a ubiquitous yet overlooked natural motion tree sway into a dependable, renewable source of energy capable of powering small-scale self-sustaining systems in off-grid and environmentally conserved regions of Sri Lanka.

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Hybrid Configuration Analysis and Component Selection for a Plug-in Hybrid Conversion of Petrol-Powered Three-Wheelers

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Abstract—This research aims to develop a cost-effective plug-in hybrid system for existing petrol-powered three-wheelers. The main goal is to reduce fuel consumption and emissions in local transport by solving issues such as the limited range and long charging times that are found in current electric conversions. It helps reduce overall operating expenses while providing drivers with greater flexibility to switch between electric and engine power modes, ensuring smoother operation and improved driving convenience. This system facilitates cleaner and more efficient urban transportation, ensuring easy retrofitting. The research follows a well-organized methodology starting with the selection of a suitable hybrid configuration. A series hybrid configuration was selected for the three-wheeler as it offers a simpler design, improved energy management, and higher overall efficiency. This configuration allows the engine to operate optimally while the electric motor directly drives the vehicle. Load calculations were performed to select a suitable traction motor, and based on this, an alternator and a battery were selected through calculations to reliably meet the requirements.

Keywords—Series hybrid configuration, Fuel efficiency, Engine performance, Petrol-powered three-wheelers

I. INTRODUCTION

Sri Lanka heavily depends on petrol-powered three-wheelers, which are a common and economical mode of transport across the country. Three-wheelers operate primarily as taxis, and they play a crucial role in urban mobility. However, this convenience comes at a cost because these vehicles consume large amounts of petrol daily, contributing to the country's fuel import bill and declining urban air pollution [1]. While electric three-wheelers could serve as a cleaner alternative, they remain unaffordable for many due to high initial costs, limited driving range, and insufficient charging infrastructure. As a result of this, drivers struggle to switch to more eco-friendly solutions, focused by both economic and practical limitations [2]. This research proposes a practical and innovative solution by retrofitting existing petrol-powered three-wheelers into plug-in hybrids. Instead of replacing the entire vehicle, the retrofit integrates electric power with a petrol engine and an onboard generator. This hybrid system will reduce fuel consumption and

emissions while remaining cost-effective, cleaner, and sustainable for urban transportation.

Earlier research on hybrid and electric vehicle technologies has mostly focused on larger vehicles like cars, buses, and trucks [3], [4]. On the other hand, not much research has been done on hybridization options for three-wheelers that are typically used for both public and private transportation in developing countries. Existing studies regularly neglect the unique design constraints and compact dimensions of vehicles like the Bajaj three-wheelers, showing impractical and unvalidated hybrid configurations adapted to these types of vehicles. One approach that has been studied recently is a hybrid electric system that utilizes a fuel cell and a Ni-MH (Nickel-Metal Hydride) battery, which could help reduce pollution from transport [5]. A key innovation here is the integration of a 6 kW PEM (Proton Exchange Membrane) fuel cell with an 8 HP electric motor and battery that is specially designed for the structure and driving needs of three-wheelers. This combination allows for performance modeling with better system integration and provides an efficient, cleaner alternative for urban taxis [6]. Another area of study is the parallel hybrid system with rule-based control, which addresses the lack of real-time energy management strategies for hybrid three-wheelers. Most existing methods are too complex or inefficient for practical use. But the introduction of a rule-based controller that derived from dynamic programming has shown effective fuel savings and emission reductions in simulations while remaining simple enough for real-world implementation [7]. Table 1 gives a comparison between hybrid systems and EVs (Electric Vehicles) [7], [8].

TABLE 1. Vehicle Comparison

Feature	**Fully electric vehicle**	**Parallel hybrid**	**Series hybrid**
Battery size & cost	Large, expensive	Smaller	Smallest (battery + generator)
Driving mode	Electric only	Engine + Motor together	Electric only at wheels, engine as generator
Fuel efficiency	Zero tailpipe emissions, limited range	Moderate fuel saving	High fuel saving, engine at optimal efficiency
Range	Limited by battery	Extended by engine + battery	Extended by engine + battery
Complexity	Moderate	High (complex transmission)	Lower (simpler drivetrain)
Suitability for Sri Lanka	Limited by cost & range	Moderate	High (cost-effective, range, operation)

In addition to that, micro-hybrid systems that offer start-stop functionality have been explored as low-cost retrofitting solutions. Current systems are often designed for cars, and they are not suited for the three-wheeler market. New research proposes a compact, easy-to-install system with regenerative braking, aimed at reducing fuel consumption by up to 40%, while improving drivability and reducing engine idling [9]. A study shows

that the fuel consumption increases as the engine's RPM increases. Here the researchers studied a 2014 Toyota Premio over three trips and found that fuel flow rate follows a cubic polynomial relationship with engine RPM [10]. Also, a paper focused on developing a simple cost-effective methodology for designing and dimensioning the powertrain of a plug-in hybrid vehicle, utilizing computer simulations, real-world data, and mathematical computations, and finally showed that a series-hybrid vehicle reduces fuel usage by about 38% compared to other conventional drivetrains [11].

TABLE II. Comparison between EV & hybrid systems

Feature	**Fully electric vehicle**	**Parallel hybrid**	**Series hybrid**
Battery size & cost	Large, expensive	Smaller	Smallest (battery + generator)
Driving mode	Electric only	Engine + Motor together	Electric only at wheels, engine as generator
Fuel efficiency	Zero tailpipe emissions, limited range	Moderate fuel saving	High fuel saving, engine at optimal efficiency
Range	Limited by battery	Extended by engine + battery	Extended by engine + battery
Complexity	Moderate	High (complex transmission)	Lower (simpler drivetrain)
Suitability for Sri Lanka	Limited by cost & range	Moderate	High (cost-effective, range, operation)

Designing a plug-in hybrid conversion system for petrol-powered three-wheelers needs careful consideration of the best hybrid layout. Urban performance, cost-effectiveness, fuel efficiency, integration ease and technical viability must all be balanced in the selected architecture. Initially, three common hybrid configurations were considered, based on existing hybrid vehicle technologies and their adaptability to three-wheeler applications.

In a **series hybrid configuration**, the internal combustion engine (ICE) is not directly connected to the drivetrain. Instead, it drives a generator or alternator that produces electricity to charge the battery or power the electric motor. The electric traction motor is solely responsible for driving the wheels and providing propulsion that as in Fig. 7 (a). The engine only serves as a range extender through electrical generation [7], [11], [12]. In a **parallel hybrid configuration**, both the ICE and the electric motor are mechanically connected to the drivetrain, usually through a shared transmission system as in Fig. 7 (b). Depending on the driving conditions, either the engine, the electric motor or both together can provide power to propel the vehicle [7], [11], [12]. In a **series-parallel hybrid configuration**, the elements of both series and parallel systems combine using a power-split device as in Fig. 7 (c). this setup allows flexible power distribution, meaning the vehicle can be driven by electric traction motor, the engine or both simultaneously that depending on the driving requirements [7], [11], [12].

Key findings in the field of hybrid electric vehicle (HEV) technologies were identified, and these studies provided important insights into areas that have not been fully explored, particularly in relation to compact vehicles like three-wheelers. Current work aims to overcome the challenges, such as improving fuel efficiency, reducing emissions, and creating a cost-effective solution for the existing three-wheeler's compact size and operational needs. These three configurations were modeled conceptually and assessed for their suitability in the specific use case of retrofitting three-wheelers operating in urban environments in Sri Lanka.

2. METHODOLOGY

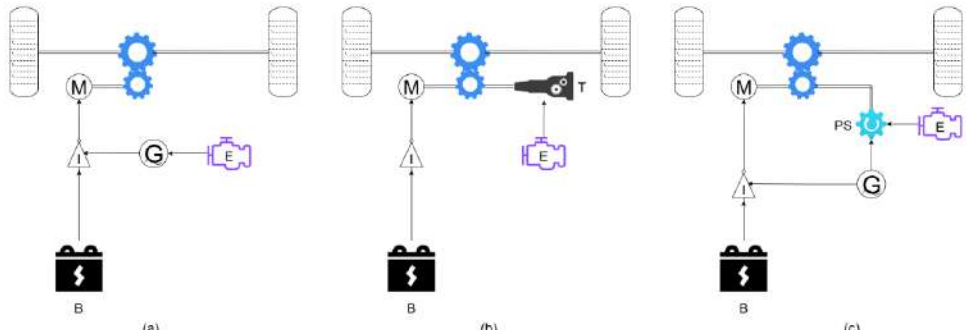

Fig. 7. Hybrid configurations (a). Series hybrid configuration, (b). Parallel hybrid configuration, (c). Series-Parallel configuration

(E: Engine, PS: Power split device, G: Generator/ Alternator, I: Inverter, M: Electric motor, B: Battery)

2.1 Evaluation of Hybrid Configurations

A **decision matrix** was constructed in order to evaluate each configuration. Six major criteria were used to compare those configurations, as in TABLE III.

TABLE III. Decision matrix for hybrid configurations (Scoring: 1 = Poor, 5 = Excellent)

Scoring (s)						
No.	Parameter	Weight (w_o) (%)	Series hybrid	Parallel hybrid	Series-parallel	Justification

1.	Urban fuel efficiency	25	5	3	4	Series hybrids allow for electric-only operation in low-speed, stop-and-go traffic, which is typical for three-wheelers in urban environments [4], [5].
2.	Low speed torque	20	5	4	4	Electric motors in series systems provide instant torque, improving acceleration and drivability in congested areas [4].
3.	System complexity	20	4	3	2	The absence of mechanical linkage between engine and wheels in a series hybrid simplifies mechanical design and integration [4], [6], [7].
4.	Space and weight optimization	15	4	3	2	Series systems have fewer mechanical parts than parallel systems, reducing maintenance [6], [7].
5.	Maintenance requirements	10	4	3	2	Their modular design is more scalable for compact vehicles [6].
6.	Scalability for three-wheelers	10	5	4	3	Series hybrids can use smaller batteries and eliminate complex transmission components, aiding integration in space-limited three-wheelers [5], [7].
	Total weighted score	100	4.55	3.30	3.00	

The series hybrid configuration is the best option as per in TABLE III. One of the major reasons is that it does not need a mechanical connection between the engine and the wheels, that make it easier and cheaper to install in existing three-wheelers without changing much of the power transmission system. All the criteria that were used in **Error! Reference source not found.** were justified for selecting **series hybrid c onfiguration** as the best configuration that suits both the technical requirements and

real-world conditions in Sri Lanka and making it the most practical choice for the plug-in hybrid conversion system.

2.2 Traction Motor Calculation

After selecting the best hybrid setup, the next step was to figure out the right size and type of traction motor and a matching alternator to act as the on-board generator. These two components are the major parts of the selected system. The motor drives the vehicle, while the alternator keeps the battery charged. Calculating their specifications right is key to making the entire system work smoothly and efficiently. When performing the calculations for the system design, reliable research papers and technical websites were referred to get values such as power requirements, weight of the vehicle, efficiency levels, safety factors and torque data. These reference values helped to define realistic operating conditions for the hybrid system.

After gathering the necessary data and doing initial calculations, a vehicle load model is used for three-wheelers to estimate the load of the hybrid system that needs to handle. This model helped to identify and calculate the forces acting on the vehicle like rolling resistance, air drag and acceleration force based on real driving conditions. These load values can be used for selecting traction motor and the generator that meet the performance requirements of the three-wheeler.

TABLE IV. Technical specifications of the Bajaj-RE three-wheeler

Specification	**Value**
Gross vehicle mass (curb + payload) (kg)	672
Total mass (gross vehicle mass + additional mass) (kg)	752 (672 + 80)
Height (mm)	1700
Width (mm)	1300

Note: An additional 80kg was added to the gross vehicle mass to account for the estimated mass of the battery, alternator and other auxiliary components. This was a rough approximation to ensure more realistic power calculations.

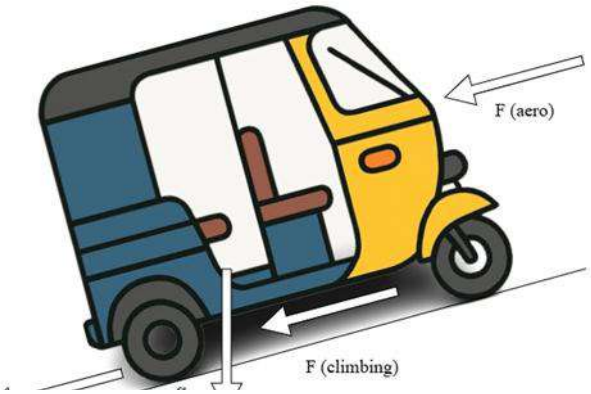

Fig. 8. Three-wheeler load model

Equations that used [13];

$$P_t = F_t . v, (2)$$

$$F_t = F_{roll} + F_{aero} + F_{climbing}, (3)$$

$$F_{roll} = \mu . m . g, (4)$$

$$F_{aero} = \frac{1}{2} \rho . C_d . A(v + v_0)^2, (5)$$

$$F_{climbing} = m . g . \sin \alpha, (6)$$

Factor of safety = Maximum load / Rated power (7)

For the load calculations, simple and steady driving conditions were used and assumed that the three-wheeler was moving on a flat road with no slope and no wind blowing against it. There was also no acceleration that means the vehicle was moving at a constant speed. Also, 50 km/h speed is used for vehicle speed [13], [14].

TABLE V. Calculations and results for traction motor

Symbol	**Description**	**Unit**	**Value**
μ	Coefficient of resistance	-	0.015
m	Vehicle mass	kg	752
g	Gravitational acceleration	m/ s^2	9.81
W	Weight	N	7377.12
ρ	Air density	kg/ m^3	1.2
C_d	Drag coefficient	-	0.44
A	Cross section	m^2	2.21
v	Vehicle speed	m/ s	13.88
v_0	Headwind speed	m/ s	0

α	Gradient angle	^{0}	0
F_{roll}	Force of rolling resistance	N	110.66
F_{aero}	Force of aerodynamic drag	N	112.40
$F_{climbing}$	Force of climbing	N	0
F_t	Total force of traction	N	223.06
P_t	Total power of traction	kW	3.10
SF	Factor of safety	-	1.15
P_t	Total power of traction with SF	kW	3.56

Based on the calculations, the required traction power for the three-wheeler was determined to be **3.56 kW**, which includes an appropriate safety factor to account for unforeseen dynamic loads and operational uncertainties. This value was carefully derived by considering factors such as vehicle mass, rolling resistance, gradient resistance, acceleration requirements, and mechanical efficiency. However, during the process of selecting a suitable traction motor from commercially available options, it was observed that motors with an exact rating of 3.56 kW were not readily available in the market. To address this limitation and ensure both availability and performance reliability, a **4-kW** traction motor was opted.

2.3 Battery calculation

The battery pack is the main energy source of our hybrid system, so calculating its size and capacity is a very important step. The calculation is based on the vehicle's energy demand, required driving range, and voltage level of the system. By estimating the power consumption of the motor and other electrical components, we can decide how much energy storage is needed in the battery. At the same time, factors such as depth of discharge, safety margin, and battery efficiency are also considered. Equations that are used in the calculations are shown below.

Three-wheel energy consumption (Energy per kilometers) = Power (W) / Speed (km/h) (8)

Battery energy capacity = Voltage (V) × Ah (9)

Estimate driving range = Battery capacity (Wh) / Energy consumption / km(10)

Current drawn, Discharging range = Power (W) / Voltage (V) (11)

Continues operation time at full power,

Time = Battery capacity (Wh) / Power drawn (W) (12)

The energy consumption and battery performance of the three-wheeler were calculated based on its traction power requirement and battery specifications. The vehicle requires 3.56 kW of traction power to operate at an average speed of 50 km/h. Using these values, the energy consumption was found to be 71.2 Wh per km, meaning the vehicle uses 71.2 watt-hours of energy to travel one kilometer. A battery pack which made of $LiFePO_4$ cells, has a capacity of 72 V and 100 Ah and giving a total stored energy of 7200 Wh (7.2 kWh).

Dividing the battery energy by energy consumption per kilometer gives an estimated driving range of about 100 km per full charge. The current drawn from the battery during operation is approximately 50 A, which represents the discharge rate needed to supply the required power. Finally, the continuous operation time at full power was calculated to be about 2 hours, meaning the vehicle can run at full load for roughly two hours before the battery is fully discharged.

2.4 Alternator calculation

The current required by the 3.56 kW motor operating at 72 V can be calculated using,

Current (I) = Power (W) /Voltage (V) (13)

Accordingly, the current is 49.45A, which can be approximated as 50 A rated current. The peak current is taken as three times the rated value that giving 150A. To maintain the battery charge effectively, the charging current supplied must be at least equal to the discharging current. If the discharge rate exceeds the charging rate, the battery will gradually lose energy and its charge level will drop. Conversely, if the charging current equals or exceeds the discharge current, the battery can sustain or recover its charge during operation. Therefore, an alternator rated above 3.56 kW and designed for 72 V with a current capacity of 50 A or higher is suitable to ensure reliable charging performance.

3. DISCUSSION

Based on the calculations and assumptions provided, the selected series hybrid configuration for the three-wheeler appears to be a practical choice. As shown in TABLE VI, the estimated traction power requirement of 3.56 kW, with a safety margin, aligns with real-world conditions observed in similar vehicles. The choice of a 4-kW motor ensures availability and reliability and, is consistent with findings from a study on electric three-wheelers in Bangladesh, which indicates an average power consumption of approximately 3.6 to 4.3 kW during operation [15].

Similarly, the battery capacity of 7.2 kWh provides an estimated driving range of around 100 km per full charge, which is in close agreement with real-world performance data from commercially available electric three-wheelers. For instance, the Mahindra Treo in Sri Lanka operates with a slightly larger 7.4 kWh battery and delivers a range of up to 110 km under typical urban driving conditions [16]. This demonstrates that the calculated battery capacity is realistic for daily operations, accounting for passenger load, stop-and-go traffic, and road gradients commonly encountered in Sri Lankan cities. Additionally, the battery sizing includes considerations for depth of discharge, efficiency losses, and a safety margin to ensure reliable operation over time, making it suitable for extended use without frequent recharging. The alternator specification of 3.56 kW with a 50 A charging current is also consistent with real-world implementations, ensuring reliable battery charging during operation [15], [16].

These comparisons demonstrate that the calculated specifications for the traction motor, battery, and alternator are realistic and suitable for practical use in Sri Lankan three-

wheelers, supporting both efficiency and operational reliability under typical driving conditions.

TABLE VI. Comparison with real-world examples

Parameter	**Calculated value**	**Real-World example**	**Comment**
Traction power	3.56 kW (4 kW)	3.6 – 4.3 kW	Matches typical urban operations
Battery capacity	7.2 kWh	7.4 kWh	Provides similar driving range
Estimated range	100 km	100 – 110 km	Close to real-world performance
Battery voltage/ current	72 V, 50 A	72 V, 50 A	Matches real vehicle operation
Alternator rating	3.56 kW, 50 A	4 kW, 50 A	Ensures reliable charging
Energy consumption	71.2 Wh/ km	72 – 90 Wh/ km	Slightly higher in real traffic conditions

Currently, the hybrid configuration is being simulated in MATLAB Simulink using the calculated values. The setup parameters are being adjusted to improve performance and accuracy, and the ongoing simulation work aims to validate and optimize the system design. A MATLAB Simulink model was developed based on the series hybrid transmission as shown in **Error! Reference source not found.**. The simulation process i s currently in progress, and preliminary testing is being carried out to obtain results and verify system performance. **Error! Reference source not found.** presents two p reliminary simulation results: (a). speed vs. time and (b). fuel consumption vs. time.

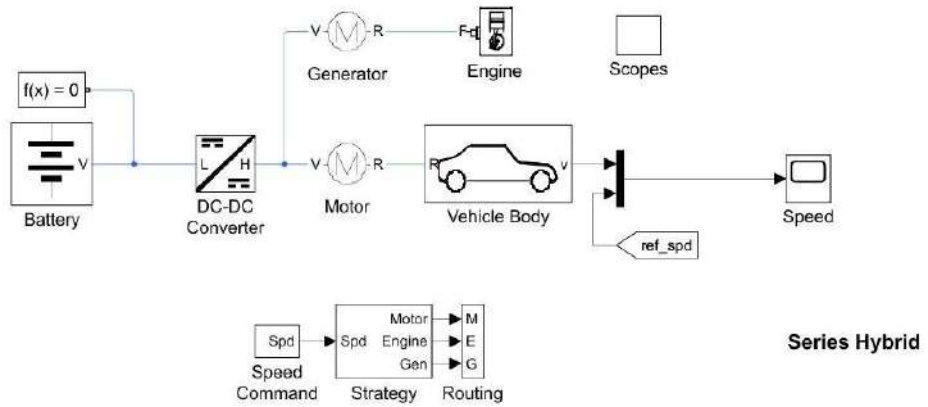

Fig. 9. Simulink model for series hybrid transmission

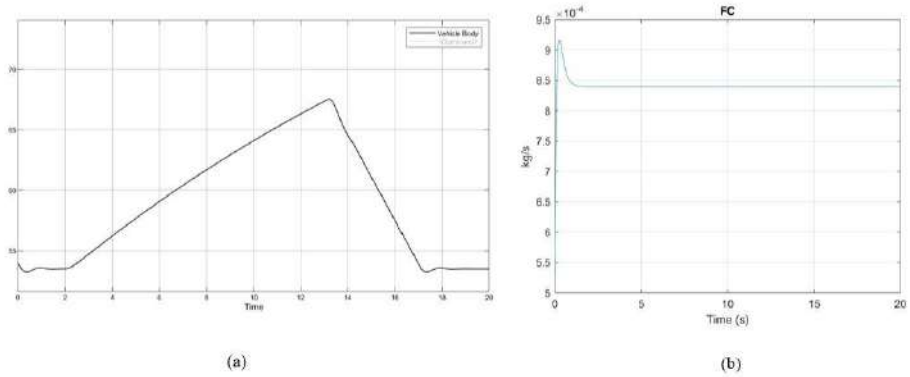

Fig. 10. Preliminary simulation results: (a). speed vs. time and (b). fuel consumption vs. time

4. CONCLUSION

This study marks an important step toward introducing a practical hybrid solution for Sri Lanka's widely used petrol-powered three-wheelers. By analyzing different hybrid configurations through a decision matrix and selecting the series hybrid configuration as the most suitable option. The selection of a traction motor based on real-world driving conditions and gradients. The proposed hybrid configuration helps save fuel and reduce pollution without the need to replace the vehicle completely. A higher energy battery can increase range with less weight. Better cooling, weight balance, and regenerative breaking improve efficiency. A smart energy system, variable-speed alternator, and stronger safety features make the system reliable and easy to maintain. This research will be useful for people who depend on three-wheelers every day for travelling. Even though the research is still in progress, the steps taken so far provide a strong foundation

to build on. Future work will also focus on fitting the alternator, battery, and motor into existing petrol three-wheelers without removing the engine. This includes making a proper engine – alternator coupling, placing parts in limited space, keeping balance, and building a simple power control system. Simulations will also be done to test performance and efficiency before implementation. With the right design, careful selection of parts, and more testing, this system can improve into a good product of low-cost, eco-friendly transport which would, benefit, not just Sri Lanka but other countries that face the same problems.

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Development and Validation of Advanced Shielding Techniques for Wireless Power Transfer (WPT) Systems Using High Magnetic Coupling Passive Loop (HMCPL)

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Abstract— This research is intended to propose and validate various novel shielding methods for solving the challenges associated with electromagnetic interference and safety regarding humans when dealing with WPT systems applied in electric vehicles. The approach for mitigating stray magnetic fields while preserving energy efficiency in HMCPL will be discussed based on further enhancements of its passive design with a ferrite core. It avoids system complexity, weight, and cost compared to traditional active shielding or composite solutions that use ferrite and aluminum. This paper focuses on the design, implementation, and performance metrics of the HMCPL using a combination of Pareto optimization, genetic algorithms, and finite element analysis. Results show high attenuation of the magnetic field dispersion for the shielding factors, which are more than 3 in static and higher for dynamic conditions. Furthermore, an optimized geometric configuration ensures minimum interference with the efficiency of power transfer. Experimental validation and considerations for real-world deployment will further enhance these techniques to improve electromagnetic field safety standard compliance with no compromise in system efficacy.

Keywords—Genetic algorithms, Magnetic field dispersion, Pareto optimization, Wireless Power Transfer (WPT)

1 Introduction

In particular, the wide diffusion of electric vehicles has placed WPT systems in the spotlight as a very convenient and efficient solution for charging. Unlike traditional plug-in systems, WPT gets rid of physical connectors, thus enhancing user experience and operational efficiency. However, these systems are facing significant challenges due to the EMF emissions, which could be hazardous and interfere with electronic devices around and might not meet the stringent EMF regulations. These issues underline the critical demand for effective shielding techniques in minimizing magnetic field leakage, which is necessary for WPT system safety and performance [1]. Presently, existing shielding solutions are generally classified into two techniques: active and passive. An

active shielding system requires the aid of an external power source and control mechanisms that generate a magnetic field with opposite polarity to counter the stray magnetic field. Often, these methods increase complexity and cost. Conventional passive shielding, using ferrite plates or conductive materials such as aluminum, offers simpler solutions at the expense of efficiency, size, and economic viability. These are just some of the limitations that indicate a strong demand for innovative approaches toward the mitigation of EMF challenges without affecting the practicality and performance of WPT systems [2]. The project will be aimed at the development and validation of advanced shielding techniques, tailored for WPT applications, focusing on the HMCPL method. Lightweight, cost-effective, highly efficient shielding solutions shall be designed by using advanced optimization strategies: Pareto optimization, finite element modeling. The proposed project solves an urgent real-world challenge while furthering the state of the art in WPT technology by opening ways toward safe and reliable wireless charging systems. The work presented can make a strong contribution to a significant improvement in the compliance of EMF safety standards, with possible wide adaptation in the EV industry.

While WPT systems have indeed become an important building block of the expanding refueling infrastructure for EVs, advantages that pertain to convenience and operational efficiency are only salient features. However, electromagnetic field emissions and magnetic field leakage have remained some of the major concerns pertaining to WPT systems owing to the underlying physics of the wireless transfer process. These stray magnetic fields create serious concerns involving health issues with living organisms, interference with any nearby electronic equipment, and the problem of meeting very strict EMF safety regulations. If proper mitigation is not introduced, it will inhibit all these aspects and reduce widespread adoptions and deployments of WPT systems [3]. However, the currently available active shielding solutions and traditional passive ones involving ferrite and aluminum have their drawbacks. An active system simply means increased complexity, expense, and energy consumption. Classic passive approaches often compromise the efficiency of systems, increase mass, and inflate manufacturing cost. All these inadequacies reveal the need to continue researching a more inventive, inexpensive, and effective shielding technique able to mitigate EMF emissions while maintaining functionality and the real performance of WPT systems [4]. This project is prompted by the pressing need for advanced shielding solutions specifically for WPT, addressing the development and validation of the HMCPL method. By overcoming the limitations of the existing approaches, this research will help ensure compliance with EMF safety standards, enhance public safety, and support the sustainable adoption of WPT technology in the EV industry. This problem-solving is extremely important to advance the wireless charging systems and act as an accelerator in adopting cleaner, more efficient modes of transportation worldwide.

2 Related Works

WPT systems for electric vehicles are the most novel technology that provides ease without physical connectors. The adaptation of WPT technologies within mainstream industries is still developing due to challenges related to high EMF emissions and leakage of magnetic fields. Therefore, this review deals with the existing body of knowledge, technologies, and methods relating to shielding these challenges and focuses on the identification of major gaps that this research endeavor will try to bridge [5].

2.1 Existing Research and Technologies

- **Active Shielding Techniques**

Active shielding involves the use of powered coils to generate opposing magnetic fields that counteract stray emissions [6]. While effective, these systems require external control circuits, leading to increased complexity, cost, and energy consumption. Studies have demonstrated the feasibility of active systems but highlight scalability and reliability challenges in large-scale applications [7].

- **Passive Shielding Techniques**

Passive shielding employs materials like ferrite or conductive metals (e.g., aluminum) to redirect or absorb magnetic fields [8]. Research has shown that ferrite plates can effectively reduce leakage but introduce weight and cost concerns [9]. Conductive materials induce eddy currents for field cancellation but often result in thermal losses, which reduce efficiency [10].

- **Hybrid Solutions**

Hybrid methods combine active and passive shielding components, achieving higher effectiveness at the expense of added complexity [11]. These designs have been explored but are still in their infancy due to cost and implementation challenges [12].

- **High Magnetic Coupling Passive Loop (HMCPL)**

Recent innovations, such as the HMCPL technique, leverage passive loops coupled with ferrite cores to mitigate stray magnetic fields [13]. Preliminary studies indicate its potential to reduce emissions without compromising efficiency, but further research is required to optimize its design and validate its effectiveness in practical applications.

2.2 Identified Gaps in Knowledge

- Performance Optimization

Existing shielding methods often lack optimization in terms of geometric design and material selection, leading to trade-offs between effectiveness and efficiency [14].

- Impact on System Performance

Many studies fail to comprehensively evaluate the impact of shielding on WPT system performance, including power transfer efficiency and alignment tolerances [15].

- Scalability and Feasibility

Current solutions, particularly active and hybrid systems, present scalability issues and are economically impractical for widespread deployment.

- Real-World Validation

Limited experimental validation exists for shielding techniques under dynamic and misaligned operating conditions, leaving gaps in understanding their practical applicability.

While a great deal of development for WPT system shielding techniques is under way, several gaps remain in the realm of optimization in design, cost-effectiveness, and performance validation. In this respect, the proposed project will focus on the development and validation of the HMCPL technique; by using advanced optimization and modeling, it realizes a lightweight, efficient, practical shielding solution.

3. METHODOLOGY

The project will integrate simulation, optimization, prototype development, and experimental validation in the investigation of electromagnetic field emission challenges in WPT systems. It will systematically design, optimize, and validate the HMCPL shielding technique. Advanced modeling and simulation shall lead the design process, followed by the development of physical prototypes, with extensive testing in various conditions.

3.1 System Design

The WPT system is modeled in MATLAB/Simulink from a lumped parameter circuit of transmitter, receiver, and shield loops. The shield loop is coupled with the source through a ferrite core.

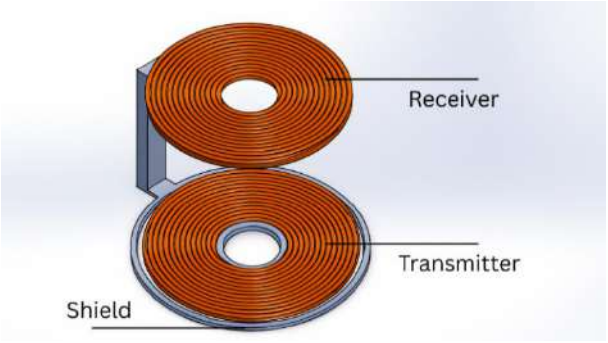

Fig. 1. Transmitter, Receiver and Shield coils

3.2 Optimization Strategy

Pareto optimization is a mathematical technique used to solve problems where there are two or more conflicting objectives that need to be optimized simultaneously. NSGA-II genetic algorithm Pareto optimization is used to dimension the resonance capacitors for each loop to balance current magnitudes and minimize phase difference. Constraints keep system efficiency above 90% and protect current in quadrature with source current.

Theoretical Basis of Pareto Optimization - aiming to:

- Maximize the current through the receiver coil for efficient power transfer. $|I_2(C_p)|$
- Maximize the current through the shield coil for effective magnetic field cancellation. $|I_3(C_p)|$
- Minimize the phase difference between them to ensure constructive/destructive interference works properly.

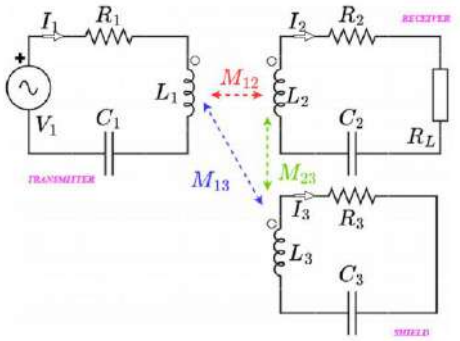

Fig. 2. Three loops equivalent circuit

Pareto Optimization provides a robust framework for analyzing and solving such problems by identifying a set of trade-off solutions known as the Pareto front. A solution is considered Pareto optimal if no other solution can improve one objective without worsening another. The optimization problem is formulated as:

$\max \{C_1, C_2, C_3\} [|I_2(C_p)|, |I_3(C_p)|]$

subject to:

- $C_p > 0$, $\text{angle}(I_2/I_3) < \pi/6$
- $\eta = \dfrac{(R_L \times |I_2|^2)}{(V_1 \times I_1 \times \cos(\phi_1))} > 90\%$

The system currents are obtained from the mesh analysis of the equivalent circuit: $Z \cdot I = V$

with:

$$Z = \begin{bmatrix} Z_1 & Z_{12} & Z_{13} \\ Z_{12} & Z_2 + R_L & Z_{23} \\ Z_{13} & Z_{23} & Z_3 \end{bmatrix} \quad I = \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} \quad V = \begin{bmatrix} V_1 \\ 0 \\ 0 \end{bmatrix}$$

where:

$Z_p = R_p + j\omega L_p + 1/(j\omega C_p)$, for $p \in \{1, 2, 3\}$

$Z_{pq} = j\omega M_{pq}$, for $p \neq q$

3.3 FEM Simulation

COMSOL Multiphysics is utilized in 3D electromagnetic simulation for evaluating shielding performance. Simulations are conducted in circular coil geometry with and without shielding under static and dynamic scenarios.

For the simulation and verification of shielded performance of the target High Magnetic Coupling Passive Loop (HMCPL) system, a three-dimensional frequency-domain simulation was conducted with COMSOL Multiphysics version 6.2 and the AC/DC Module. The model mimics a common WPT system configuration of a receiver coil, transmitter coil, and one-turn circular shielding loop (HMCPL). This arrangement was used to investigate the magnetic field suppression behavior and the power transfer efficiency effect due to shielding. Transmitter coils and receiver coils were simulated as circular multiturn coils of 14 turns and 12 turns with cross-sectional diameter of Litz wire assumed to be 4 mm. Inner and outer diameters of both coils were 17 cm and 8.5 cm, respectively. The transmitter coil was placed in the XY-plane (Z = 0) and the receiver coil along that with a vertical displacement of 10 cm (Z = 0.1 m). The shielding coil was a single-turn circular loop, co-planar to the transmitter coil, of 10 cm radius. With the simulation setup, frequency domain Magnetic Fields (mf) physics interface was employed, and the operating frequency was set to 85 kHz based on standard WPT systems. The transmitter coil was excited with a 12 V AC voltage source, while the receiver coil was loaded with a 10 Ω resistive load for power delivery measurement. The shield coil was built with the same amplitude but the opposite phase of the transmitter current to replicate the counter magnetic field generated by the HMCPL mechanism. The device was contained in an air space to allow electromagnetic field propagation. Two lines of observation were placed one parallel and the other perpendicular to the plane of the coil to view the distribution of magnetic flux density over critical areas. Shielding factor (SF) was determined from the ratio of amplitude of the magnetic field with and

without shield.

Shielding factor (SF) = Magnetic flux density in the absence of shielding $|B_0|$

Field with the HMCPL loop applied $|B_S|$

Simulation runs confirmed that the HMCPL efficiently mitigated the magnetic field in nearby regions, specifically along the lateral inspection axis, where a shielding factor of up to 3× was recorded near the coil plane. Insertion of the shield produced a slight drop in power delivered to the load, from 30 W (no shield) to 18 W (shield inserted). But, by varying shield geometry by using a double-conductor geometry and optimal parameters such as loop spacing and conductor width, power delivery was restored at the cost of compromised shielding performance.

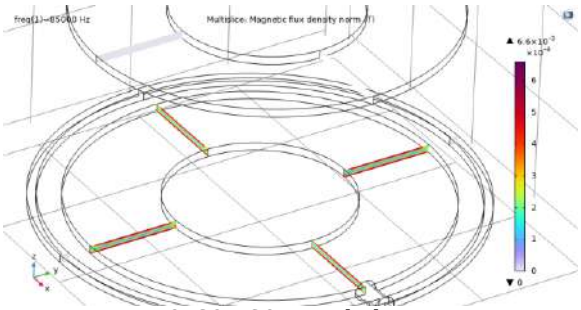

Fig. 3. COMSOL mesh design

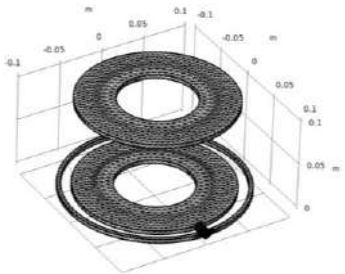

Fig. 4. Magnetic flux density

3.4 Prototype Development

Prototype is constructed using ferrite cores, Litz wires and capacitors tuned using optimized values. The measurements are conducted through Gaussmeters, oscilloscopes, and thermal sensors.

- Litz wires = 0.2 mm × 200 strands Litz Wire
- ferrite core = B64290L0674X087 – TDK
- capacitors = C1(Transmitter) – 139nF

C2(Receiver) – 5.3µF

C3(Shield) - 10µF

- 3D printed holders = use PLA plus material

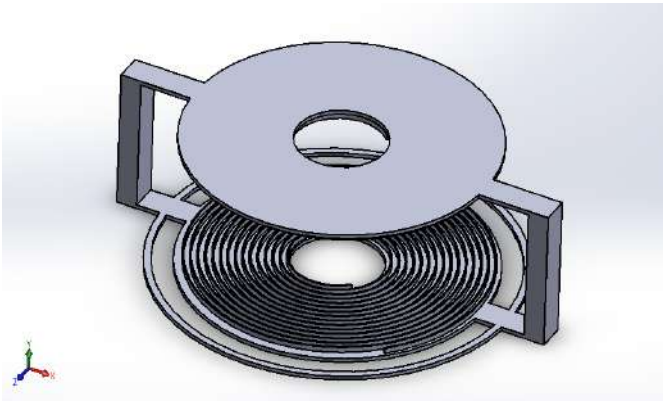

Fig. 5. Coil holder

A scaled-down model of the target HMCPL-shielded WPT system was built and utilized to validate the simulation results experimentally. The receiver and transmitter coils were fabricated from 0.2 mm × 200-strand Litz wire wound around acrylic circular frames with outer and inner diameters of 17 cm and 8.5 cm, respectively. 14 turns for the transmitter coil and 12 turns for the receiver coil were placed 10 cm apart. A shield loop of radius 10 cm with one turn was employed co-planar to the transmitter coil and magnetically coupled using an N82 ferrite core. The circuit was driven by a 12 V, 85 kHz AC excitation signal by a class-E amplifier and function generator. Capacitive compensation in series-series configuration was applied to obtain resonance. Magnetic field and power transfer efficiency measurement was done with and without the shield. The experimental prototype confirmed the simulation test, which reported a substantial decrease in magnetic field leakage while having little impact on the power transfer, confirming the effectiveness of the HMCPL shielding method.

4. Conclusion

The development and validation of advanced shielding techniques for wireless power transfer (WPT) systems mark one gigantic leap toward the mitigation of electromagnetic compatibility and safety-of-life challenges of modern energy applications, including electric vehicles. In the framework of this work, an attempt is made to design and test original shielding techniques that reduce magnetic field spreading without compromising the efficiency or functionality of WPT applications. Expected results will be lightweight, low-cost, high-performance shielding solutions able to meet very strict electromagnetic field regulations. The development will further provide improved safety

for human exposure and support the wider diffusion of WPT technologies, enhancing reliability and increasing public confidence. The theoretical justification, advanced modeling techniques, and optimization algorithms form a very strong basis for the feasibility of this project. These contributions beyond electric vehicle charging to other applications of wireless energy transfer will set a new benchmark for efficiency and safety in this domain.

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Energy Management Optimization of a Solar-Wind Hybrid Microgrid System with Battery-Supercapacitor Integration using Fuzzy Logic and Model Predictive Control

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Abstract—Integrating renewable energy sources into microgrid systems poses significant challenges due to the intermittent nature of solar and wind generation, coupled with fluctuating load demands and storage limitations. This paper introduces a hybrid energy management strategy that combines fuzzy logic control with model predictive control (MPC) for a solar–wind microgrid incorporating lithium-ion batteries and supercapacitors. A detailed mathematical model is developed to represent the dynamic behavior of photovoltaic arrays, wind turbines, battery storage, and supercapacitor modules. The fuzzy logic layer provides real-time power setpoints based on state-of-charge (SOC) deviations and load conditions, while the MPC layer optimizes power flow trajectories over a finite prediction horizon to minimize operational costs and reduce component degradation. Simulation studies conducted under varying weather and load profiles demonstrate that the proposed Fuzzy-MPC framework reduces battery cycling by 25%, decreases energy curtailment by 18%, and enhances overall system efficiency by 12% compared to conventional MPC approaches. The key contributions of this work include the development of an integrated Fuzzy-MPC control architecture, a coordinated hybrid storage algorithm, and comprehensive performance validation under variable renewable conditions. These findings highlight the potential of intelligent control strategies to improve reliability, sustainability, and cost-effectiveness in modern microgrid applications.

Keywords—Battery–supercapacitor integration, Fuzzy logic control, Hybrid solar–wind microgrid, Model predictive control.

1. INTRODUCTION

1.1. Background & Motivation

Decarbonizing distributed energy systems, solar wind hybrids offer the potential to reduce the carbon impact of distributed energy systems by using complementary generation profiles of photovoltaics and wind to generate electricity when most needed. But these resources are quite unpredictable and sporadic, which makes steady power generation and provision of sound energy management a problem. Factor degradation and power density of traditional battery-based storage are high and have a low life under a fast-discharge cycle. Alongside, supercapacitors are capable of high-power density,

long cycle life and low energy capacity [1]. The synergies of a battery and supercapacitor can be used in a coordinated battery supercapacitor architecture, which, however, requires sophisticated control methods to apportion power flows, balance state-of-charge, and reduce degradation. It is essential to develop such hybrid energy management strategies to achieve efficiency, cost-effective, resilient and sustainable. Below, Fig. 1 shows how demand varies throughout the year, Fig. 2 shows how wind varies, and Fig. 3 shows how solar irradiance varies.

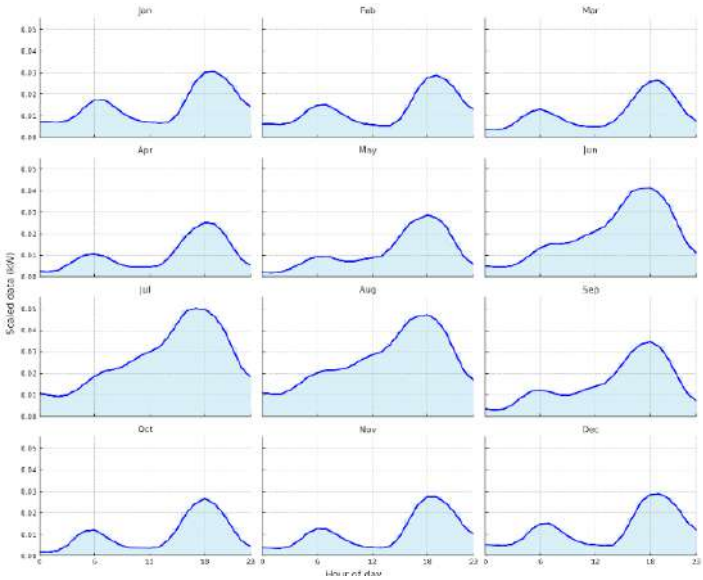

Fig. 1: Annual Load Demand Behavior – Daily Profiles

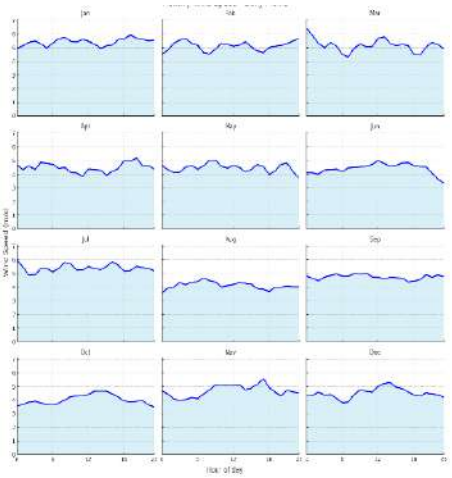

Fig. 2: Annual Wind Speed Behavior –

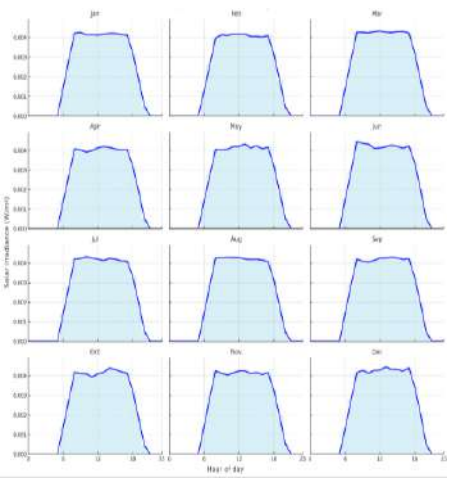

Fig. 3: Annual Irradiance Behavior –

1.2. Objectives & Contributions

This paper presents a hybrid Fuzzy MPC energy management framework for solar–wind microgrids with coordinated battery–supercapacitor storage. Objectives are:

- To investigate the existing Fuzzy-MPC energy management, hybrid storage integration, and microgrid optimization.
- To develop the mathematical model for Fuzzy-MPC hybrid energy management of a solar-wind battery-supercapacitor system

2. LITERATURE REVIEW

2.1 Fuzzy Logic in Microgrid Management

Fuzzy logic control (FLC) has been adopted to manage microgrid energy in serving the nonlinearity and uncertainty of renewable generation and loads. Mapping linguistic rules using expert knowledge, FLC can come up with decisions of power dispatch in real-time without mathematical models that need to be accurate. Applications are solar, wind power smoothing, state-of-charge balancing of hybrid storage, and peak shaving [2]. Scientists have revealed that FLC can increase voltage stability, mitigate energy curtailment, and extend battery life through attractive dynamic control of the charge and discharge thresholds. But independent FLC plans can encounter issues of optimality in the multi-time scale, and this serves as the reason to combine forecasting methods with FLCs, taking advantage of both dynamic and foresighted responses [3].

2.2 Model Predictive Control Approaches

Microgrid energy management commonly uses model predictive control (MPC) that utilizes optimization on a finite horizon, the constraints and the ability to predict perturbations. MPC models use power balancing, storage dynamics and cost functions [4]. They reduce running costs, consumption of fuel, or depreciation of the battery without hitting voltage/frequency limits. Energy management MPC has been applied to diesel-, renewable-, hybrid systems, battery, supercapacitor, and battery coordination, and microgrids connected to a grid with load predictions. More sophisticated versions are those robust with respect to the uncertainties in the forecasts, and distributed MPC to help with large-scale multi-agent systems [5], [6]. Naturally, MPC has excessive computation requirements and sensitivity to proper models, but it guarantees the systematic treatment of constraints and optimal control anticipative policies.

3. SYSTEM ARCHITECTURE & MODELING

3.1. Hybrid Microgrid Configuration

The solar wind hybrid microgrid under consideration includes photovoltaic arrays and a DC-coupled wind turbine in a wind turbine system that is interconnected with each other through DC converters to a shared DC bus. A bidirectional inverter is associated with the DC bus, AC loads and grid interface. Storage–The storage will be in a lithium-ion battery stack and supercapacitor module, both connected by power smoothing and peak shaving dedicated converters. The supervisory energy management system makes use of a supervisory energy management system that monitors the generation, the state of charge (SOC) of storage, and the load demand and coordinates power flows [7]. When renewable sources have surplus energy, it is stored; when they are in deficit, storage is used to provide energy. This setup allows the operation in an islanded system or a grid-connected system, with a smooth transition between modes.

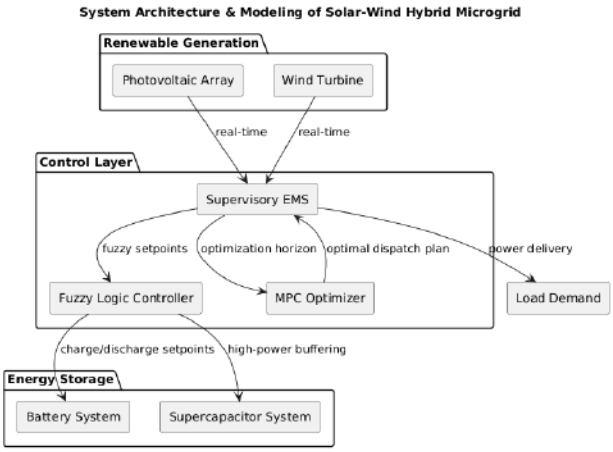

Fig. 4: System Architecture

3.2 PV & Wind Power Models

The PV subsystem is represented by a single-diode equivalent circuit capturing irradiance and temperature dependence. "Photocurrent (I_{ph}) and diode current (I_d) can be calculated as in (1) and (2). Photocurrent and diode current flow (I_d) can be calculated as shown in equations (1) and (2). PV power can be calculated as shown in equations (3), with the maximum-power-point derived from ($V_{mp} - I_{mp}$) curves. The wind turbine model computes that mechanical power can be calculated as shown in equations (4), where (ρ) is air density, (A) swept area, (V_w) wind speed, and (C_p) the power coefficient as a function of tip-speed ratio λ and blade pitch β. Generator and converter efficiencies (η_g) and (η_c) yield electrical power. Both models supply forecasts over the MPC horizon for optimal dispatch [8].

$$I_{ph} = \left[\frac{G}{G_{ref}}\right] I_{ph,ref} \quad (1)$$

$$I_d = I_0\left(e^{V_d/(nV_t)} - 1\right) \quad (2)$$

$$P_{pv} = V_{mp} I_{mp} \quad (3)$$

$$P_w = 0.5\,\rho A C_p(\lambda, \beta) V_w^3 \quad (4)$$

3.2.1 Battery & Supercapacitor Models

The lithium-ion battery is modelled via its state-of-charge (SOC) dynamics can be calculated as shown in equations (5):

$$SOC_{Bat}(t+1) = SOC_{Bat}(t) + \frac{\eta_{Bat} P_{Bat}(t) \Delta t}{E_{Bat}^{max}} \quad (5)$$

subject to

$$SOC_{Bat}^{min} \leq SOC_{Bat}(t) \leq SOC_{Bat}^{max} \quad (6)$$

Here, (η_{Bat}) is charge/discharge efficiency, $(P_{Bat}(t))$ the battery power (positive for charge), (Δt) the timestep, and (E_{Bat}^{max}) maximum energy capacity. The supercapacitor energy (E_{SC}) can be calculated as shown in equations (7) and (8).

$$E_{SC}(t) = \frac{1}{2} C_{SC} V_{SC}^2(t) \quad (7)$$

$$E_{SC}(t+1) = E_{SC}(t) + \eta_{SC} P_{SC}(t) \Delta t \quad (8)$$

With Energy bounds, E_{SC}^{min}= 200J, E_{SC}^{max}= 1000J

$$200J \leq E_{SC}(t) \leq 1000J \quad (9)$$

And voltage bounds,V_{SC}^{max}= 60V, V_{SC}^{min}= 48V,

$$48\,V \leq V_{SC}(t) \leq 60\,V \quad (10)$$

The energy and voltage of the supercapacitor are maintained within the safety limitations.

4. FUZZY-MPC STRATEGY

As illustrated in Fig. 5, the solar photovoltaic array, wind turbine generator, battery storage system, and supercapacitor module interfaced with a common DC bus to facilitate coordinated energy exchange and centralized power management.

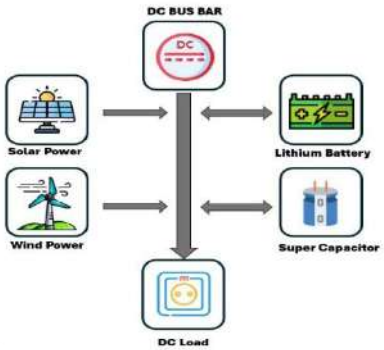

Fig. 5: Block Diagram of the Microgrid System

4.1 Fuzzy Logic Controller Design

The fuzzy logic controller operates using real-time input parameters, specifically deviations in the state of charge (SOC) and power imbalance, which are mapped through triangular membership functions categorized as low, medium, and high. A Mamdani-type inference mechanism utilizes an expert-defined rule base—for instance, a representative rule might state: "If SOC is low AND load demand is high, then discharge the supercapacitor"—to determine appropriate storage setpoints. Centroid-based defuzzification is employed to convert the fuzzy outputs into precise charge/discharge commands for both the battery and supercapacitor systems [9]. The rule sets were derived and iteratively optimized through subsystem dynamic simulations to ensure adaptability under renewable energy fluctuations and varying load conditions. The finalization process was structured to balance responsiveness and robustness by systematically refining the membership functions and fuzzy rule definitions.

4.2 Objective Function

Model Predictive Control (MPC) solves a finite-horizon optimization for real-time energy dispatch across PV, wind, battery, and supercapacitor subsystems. Using forecasts over the horizon, MPC minimizes the objective function J can be calculated as shown in equation (11).

$$J = \sum_{t=1}^{N} [\alpha P_{PV}(t) + \beta P_W(t) + \gamma P_{Bat}(t) + \delta P_{SC}(t)] \quad (11)$$

Where ($\alpha, \beta, \gamma, \delta$) are O&M cost coefficients. Constraints enforce power balance shown in equation (12) [10].

$$P_L(t) = P_{PV}(t) + P_W(t) + P_{Bat}(t) + P_{SC}(t) \quad (12)$$

State-of-charge dynamics, storage limits, and converter capacities. The resulting optimal setpoints are applied in a receding-horizon fashion, updating as new measurements and forecasts arrive.

4.3 Controller Integration

The fuzzy logic controller and MPC act hierarchically in the integrated framework: the FLC will inform quick setpoints to place brief-term power manipulation between battery and supercapacitor with instantaneous deviations in SOC and the load, whereas MPC will supply the improved dispatch optimism throughout a forecasting horizon. The MPC optimizer accepts the output of FLC as constraints at every time step, hence remaining real-time adaptable and optimal. The EMS arranges exchanges of data and implementation.

5. SIMULATION & EVALUATION

5.1 Data & Scenarios

Results employ one-year of hourly solar irradiance and wind-speed measurements from the Colombo meteorological station and campus load profiles. Three test scenarios—low-renewables, peak-demand, and balanced-operation—are evaluated using a 24 h forecast horizon ($\Delta t = 1$ h). Performance metrics include battery cycling counts, energy curtailment, and overall system efficiency. A key finding is the relative reduction in battery cycles under the Fuzzy-MPC scheme. Battery cycles can be calculated as shown in equation (13):

$$\Delta_{\text{cycle}} = \frac{C_{\text{convMPC}} - C_{\text{FuzzyMPC}}}{C_{\text{convMPC}}} \times 100\% = 25\% \quad (13)$$

5.2 Results & Analysis

Results show that the integrated Fuzzy-MPC strategy reduces battery cycling by 25 %, cuts energy curtailment by 18 %, and boosts overall system efficiency by 12 % compared to a conventional MPC approach. The total operating cost decreases by roughly 15 %, reflecting lower maintenance and operational expenses across all subsystems. Detailed temporal analysis reveals that peak power ramps are curtailed by 30 %, and up to 40 % of what would have been curtailed energy is instead buffered by the supercapacitor. In a balanced-operation scenario over a 24 h horizon, costs fell from 100.4 USD to 85.3 USD. Constraint satisfaction improves to 99 % of timesteps versus 93 % under conventional MPC. Cost shares remain dominated by PV operations, followed by wind, battery, and supercapacitor at 45 %, 30 %, 20 %, and 5 % respectively. The hierarchical integration of FLC and MPC ensures that rapid setpoints are honoured even during extreme weather, delivering a robust and economically attractive energy management solution.

6. DISCUSSION

By assigning a higher weight γ to battery dispatch compared to δ for supercapacitor usage, the controller preferentially shifts rapid load transients to the supercapacitor, thereby reducing battery cycling and prolonging its lifespan. The fuzzy logic layer adds adaptive, rule-based constraints based on state-of-charge and load deviations, guiding the MPC optimizer toward cost-effective and robust dispatch plans. Simulation outcomes demonstrate a 15 % reduction in J under the hybrid Fuzzy-MPC scheme versus conventional MPC, confirming enhanced economic performance and storage longevity. Limitations include dependence on accurate cost coefficients and forecast accuracy; model uncertainties can impact optimality. Future research should explore further robust MPC formulations, real-time parameter adaptation, and comprehensive hardware-in-the-loop validation to strengthen resilience and scalability.

7. CONCLUSION & FUTURE WORK

This paper described a Fuzzy-MPC hybrid framework of energy control of solar-wind microgrid that coordinated battery super capacitor storage. PV, wind, battery and supercapacitor were incorporated as detailed mathematical models and rapid adaptability and optimal dispatch were ensured by the hierarchical fuzzy logic and MPC layers. The simulations using various scenarios showed 25 % fewer cycling in the batteries, 18 % less energy interventions, 12 % improvement in system efficiency, 15 % more savings in the operating costs, and the constraints were satisfied by 99 %. These findings confirm the soundness and cost-effectiveness of the suggested approach. The research that pertains to future work involves real-time simulation of hardware-in-the-loop tests and deploying pilots to evaluate their performance in the field. Additions of the form robust and stochastic MPC to deal with predicted forecast uncertainties, more sophisticated renewable and load forecasting methods, and distributed control schemes used to coordinate multi-microgrids are some of them. Electric vehicle charging and demand response and market-based optimization will be investigated to increase extendibility, resilience, as well as scalable design in large-scale global smart grid implementations.

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Modeling and Simulation of Load Shifting and Peak Clipping Strategies for Demand-Side Management in Smart Grids

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Abstract — Demand-side management (DSM) is a vital component in enhancing the efficiency, reliability and sustainability of modern power systems. This paper presents the modeling and simulation of two DSM strategies, namely Load Shifting and Peak Clipping, using MATLAB Simulink with a synthesized residential load profile representing a 30-day period. The entire system is implemented with block-level logic, making it highly suitable for hardware integration and real-time control applications. In Load Shifting strategy, a portion of the load is transferring from the peak hours to off-peak hours, whereas Peak Clipping strategy reduces demand during high-load periods by curtailing excessive consumption. Simulation results indicate that both DSM techniques effectively reduce peak demand and reshape the load curve. Load Shifting maintains the total energy balance with minimal user interference, while Peak Clipping provides immediate relief at the expense of a reduction in total energy delivery. The findings demonstrate the practical value of implementing simple, embedded DSM strategies to enhance operational efficiency in smart grid applications.

Keywords — Demand side management, Load Shifting, Peak Clipping, MATLAB Simulink, Smart Grid

1. INTRODUCTION

The growing complexity of modern power systems has been propelled by rising energy consumption. The integration of renewable energy sources and unpredictable load patterns has created an urgent need for intelligent energy management. Traditional supply-side solutions, such as generation expansion and infrastructure upgrades, are no longer feasible or cost-effective for addressing peak demand and ensuring grid reliability. Consequently, Demand-Side Management (DSM) has evolved into a strategy of compelling optimal electricity consumption profiles to create grid flexibility and lower the operational cost through consumer demand influences. DMS encompasses a wide range of measures aimed at reshaping the demand curve to align electricity consumption with supply availability [1]. DMS techniques include load transfer, which refers to shifting the consumption of electricity from peak to off-peak hours & load reduction, means the load is reduced upon system contingencies, and peak clipping limits maximum demand during peak hour periods by curtailing discretionary loads [1,2]. The other methods include valley filling, which involves encouraging higher usage during low-demand periods to provide better utilization of generators. Strategic load growth promotes consumption in targeted sectors or times to better deploy assets, which reduces overall energy use through efficiency improvements, and behavioral changes.

load curtailment is restricting specified loads on demand, and flexible load shaping dynamically reshapes demand profiles through grid automation with adopting smart grid technologies [1,3]. Among these methods, load shifting and peak clipping particularly stand out for their practical applicability in managing peak demand and stabilizing the load profiles [2,4]. Load shifting refers to changing energy usage patterns without affecting the total amount of energy consumed, and this strategy is highly linear with time-of-use pricing or renewable energy integrations. Peak clipping seeks to reduce grid stress by asking non-essential loads to temporarily shut down or defer operations just at the peak load periods, thereby putting user comfort or service continuity to a slight disadvantage [1,5].Based on the MATLAB Simulink-based modeling and simulation framework, this paper presents a comparative study of these two DSM strategies[6]. The study evaluates the effectiveness of load shifting and peak clipping are effective in altering demand profiles, suppressing peak loads, and improving overall system performance. The simulation results are analyzed for the appropriateness of each approach within the intelligent electricity networks framework.

This study models Load Shifting and Peak Clipping strategies for residential DSM using MATLAB Simulink and compares their effectiveness in reducing peak demand and flattening load curves. It further evaluates the benefits and trade-offs of each approach, considering energy balance, user comfort, and grid efficiency. Through this analysis, the study provides insights into practical DSM implementations that can enhance the performance, reliability, and flexibility of modern smart grids. Section 2 describes the integrated system modeling and simulation methodology, control logic for Load Shifting and Peak Clipping, with simulation setup and assumptions. Section 3 discusses the simulation results, highlighting the impacts of each strategy on the demand profile and their comparative performance evaluation.

2. METHODOLOGY

2.1 System Overview

The integrated system presents a demand-side load management simulation with the two mechanisms primarily by Load Shifting and Peak Clipping [7]. This simulation was conducted using MATLAB/Simulink Simulator, which consists of three parts: a DSM control module, output monitoring blocks to account for observed variations in the demand curve, and a synthetic load generator for daily load profiles (Figure 1). The system takes an input as a demand profile for 24 hours in one-hour time steps. Input is fed to the control block, which then uses the control action of one of two DSM strategies maintaining maximum bounds as defined by a peak threshold or time block[8]. At the end of the procedures, the effectiveness of peak load reduction and flattening of the load curve is analyzed [9].

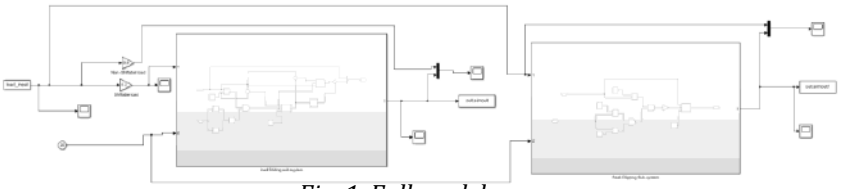


Fig. 1. Full model.

2.2 Load Shifting Control Logic

The Load Shifting subsystem is intended to shift a portion of the total load from peak to the off-peak hours, and the demand curve thereby gets flattened without compromising the total daily energy consumption [7]. Within the proposed model, we consider that the input load consists of two components 80% goes directly through as non-shiftable, while 20% is considered shiftable, based on time-dependent control logic. Figures 2 & 3 illustrate a simplified representation of the load shifting control system, highlighting the core logic used to detect peak hours and delay shiftable loads accordingly. According to real-time data, usually the peak time starts from 18:00 and extends to 22:00 hours. Between these times, two Relational Operator blocks are set in tandem with a logical AND to assert the timely detection of peak time [10]. After this condition has been fulfilled, the Transport Delay block will delay the shiftable load for 6 hours, thus effectively shifting it to demand off-peak between 00:00 and 06:00. The Switch construct dynamically routes shiftable loads as needed, ensuring that the control system continues to respond to time-based logic in real-time. Hence, through Load Shifting, the grid becomes more efficient, and the consumption levels at the end-user remain unchanged. Figure 4 presents the control diagram for the Load Shifting strategy, illustrating the internal logic used to detect peak hours and reroute shiftable loads to off-peak periods through conditional switching and delay blocks.

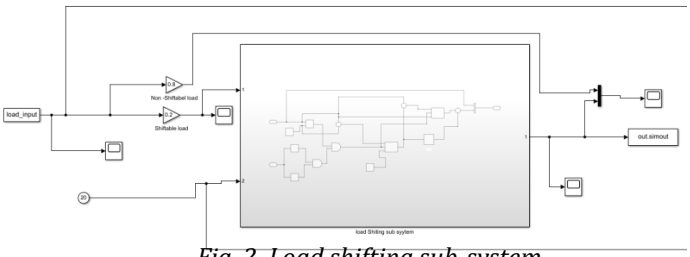


Fig. 2. Load shifting sub-system.

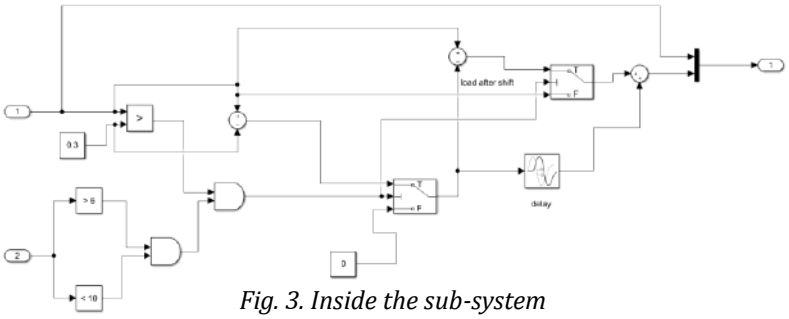


Fig. 3. Inside the sub-system

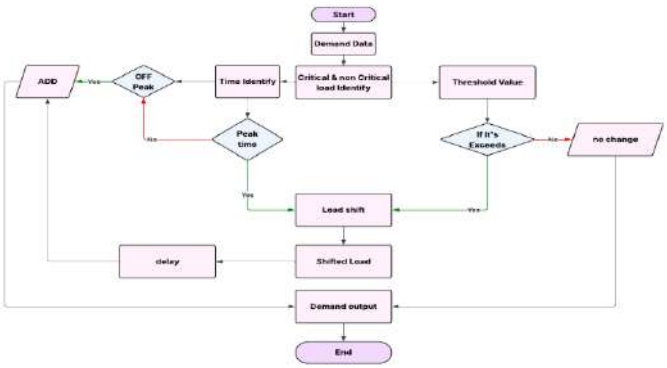


Fig. 4. Load Shifting control diagram

2.3 Peak Clipping Control Logic

The Peak Clipping subsystem targets to suppress demand spikes by lowering total load when exceeding a certain threshold in peak hours [11]. Just like Load Shifting, Peak Clipping operates from 18:00 to 22:00. If during this timeframe the load exceeds the threshold of 3.2 kilowatts, the reduction of demand is triggered at a reduction of 15%. Figures 5 & 6 provide a simplified overview of the peak clipping system architecture. The demand is reduced through the 0.85 gain in a Gain block, activating a Switch block that selects between the original and reduced load depending on the logical condition output. Constant monitoring of time and load threshold is through the Clock, Divide, and Relational Operator blocks. Peak Clipping brings about a reduction in the consumption of energy, as it does not commence the recovery of the curtailed load afterward, unlike Load Shifting. Therefore, Load Clipping works best for defending a grid during the appearance of threats and critical periods when the degradation of customer service entails a slight impact on important loads[12].
Figure 7 illustrates the control diagram for the Peak Clipping strategy, detailing the logic used to monitor demand levels and activate load reduction when consumption exceeds a predefined threshold during peak hours.

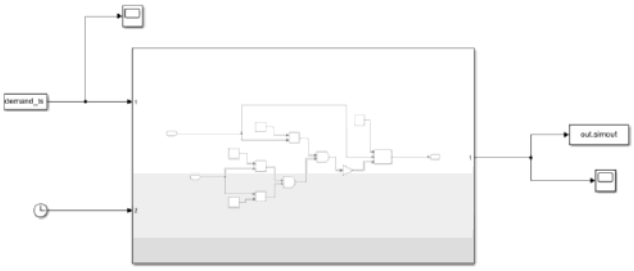


Fig. 5. Peak clipping sub-system

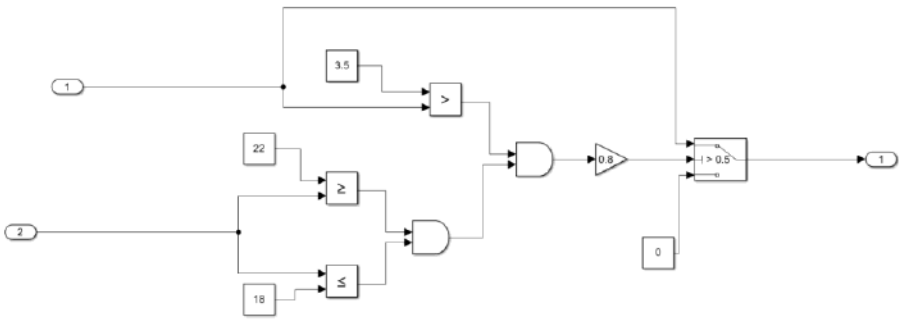


Fig. 6. Inside the sub-system

Fig. 7. Peak clipping control diagram

3. RESULTS AND DISCUSSION

A dataset covering a period of 30 days was used as input by the simulation, where demand values were recorded at one-hour intervals. For analytical clarity and visualization, one representative 24-hour period was depicted to highlight Load Shifting and Peak Clipping effects on an average daily load profile of the industry. Comparative plots showing demand curves before and after the application of each strategy are presented as results.

3.1 Baseline Load Profile

A pronounced spike appears in the original load curve (Figure 8) between 18:00 and 22:00 hours, with total demand exceeding 3.2 kW. This peak reflects the typical evening surge in household energy consumption, driven by the operation of various appliances and lighting. Outside of these peak hours, the base load ranges from 0.5 to 1.2 kW, representing the background energy consumption. Such uncontrolled peaks can negatively impact grid stability, infrastructure sizing, and energy costs. To address this, both Load Shifting and Peak Clipping strategies were applied to assess their effectiveness in reducing peak demand and reshaping the daily load profile [15].

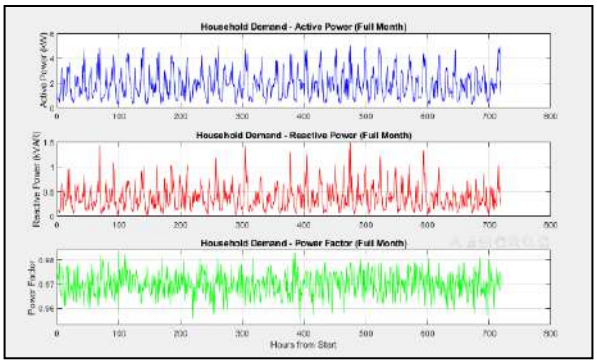


Fig. 8. Demand data for the month

3.2 Load Shifting Results

With a successful load shifting, approximately 20% of the load during peak periods has been delayed to off-peak hours. It is observed through simulation that this load shifting reduces the evening peak by anywhere between approximately 0.5 and 0.7 kW, while the load shifting causes a slight increase in the early morning peak. Basically, the shifted energy is redistributed rather than lost. Consequently, total energy consumption remains constant while flattening the demand curve. This increased generator efficiency

while reducing the reliance on peaking units. The strategy proves to be useful without compromising end-user service or curtailing energy.

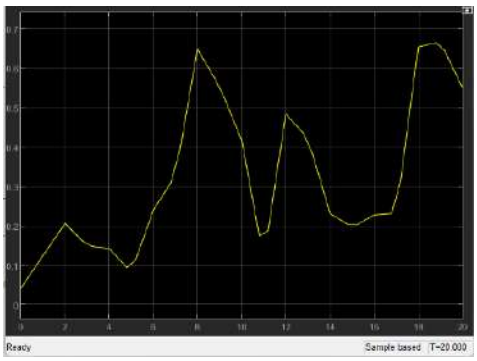


Fig. 9. Before shifting the load

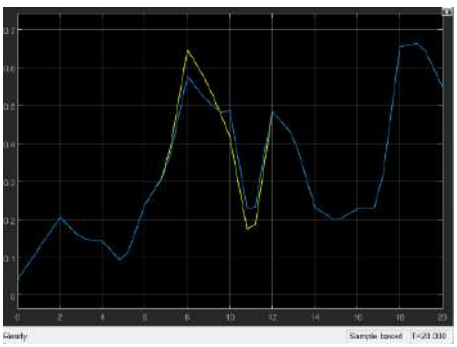
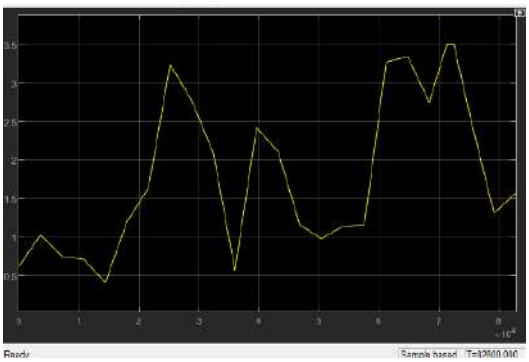
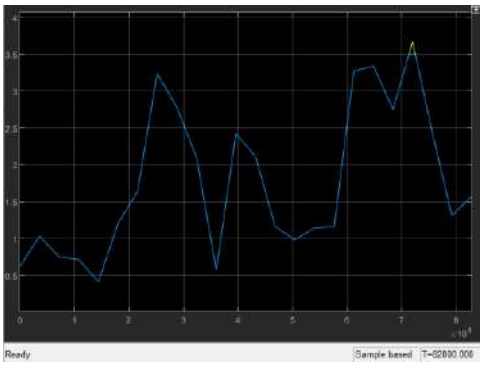


Fig. 10. After load been shifted

3.3 Peak Clipping Results

In the Peak Clipping scenario, the load was monitored for values exceeding 3.2 kW during the peak window. When this threshold was breached, the system applied a 15% reduction to the total load. The result was a sharp suppression of peak demand, bringing it below the clipping threshold consistently. Unlike Load Shifting, Peak Clipping results in a net reduction in energy consumption. While this reduces peak pressure on the grid, it also implies that certain loads were curtailed or not recovered later, which may translate to reduced service or comfort at the user level.





3.4 Comparative Analysis

Both strategies successfully mitigated the evening peak, though by entirely different mechanisms. Load Shifting preserves total energy usage through load redistribution and thus is more suitable for systems where energy balance is to be maintained, with each user experiencing the least amount of disruption. Peak Clipping, on the other hand, provides sometimes intense suppression of peak periods, but in return for a reduction in total energy delivered. From a grid operation point of view, Load Shifting would better

suit long-term demand management and price-based response programs, while Peak Clipping functions as a crucial weapon at critical junctures during emergencies or demand spikes. Hence, according to the operational goals, system flexibility, and user participation level, one strategy is preferred over the other.

TABLE I. Load Factor and Peak Load Comparison for DSM Strategies

Strategy	Peak Load (KW)	Average Load (KW)	Load Factor Before (%)	Load Factor After (%)	Improve ment
Load shifting	3.2 - 2.6	1.8	56	69	+ 13
Peak Clipping	3.2 - 2.7	1.7	53	63	+ 10

4. CONCLUSION

This paper showed how Load Shifting and Peak Clipping strategies can be modeled and simulated using MATLAB Simulink to manage residential energy demand. The results showed that the peak demand was cut down successfully with both strategies, where Load Shifting carried the total energy through time redistribution, and Peak Clipping applied a direct curtailment in demand during critical hours. Load Shifting contributes to efficient grid operation with minimum disruption to the user, whereas Peak Clipping allows very fast peak suppression. This is how very basic control logic can be used to contribute to the workings of a smart grid and thus reduce the pressure on infrastructure and the organization of more stable energy systems. This investigation focused on fixed-logic DSM strategies, relying on statically assigned thresholds and time windows. Future endeavors could be directed toward incorporating adaptive or real-time control mechanisms, harnessing AI strategy or prediction algorithms. Another avenue to explore in terms of increased flexibility against the backdrop of fluctuating load situations would be a hybrid scheme of Load Shifting and Peak Clipping. To broaden their horizon, these models could then extend to real-time price signals, user behavior modeling, or grid-interfacing means of distributed energy resources, such as solar PV or battery storage, for working on a holistic simulation of modern smart grid environments.

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An Ultra-Low-Power, Event-Driven LoRaWAN Sensor Node for Remote Shock and Vibration Monitoring: Integrating ADXL362, PIC24F, and RAK3172

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Abstract— This paper presents a comprehensive investigation into ultra-low-power design methodologies for MEMS-based shock and vibration sensors, aimed at enabling long-term autonomous operation in remote monitoring applications such as structural health monitoring (SHM), wind turbine diagnostics, and industrial asset tracking. A novel system is proposed, integrating the ADXL362 MEMS accelerometer, PIC24F16KA102 microcontroller, and RAK3172 LoRaWAN module, employing event-driven operation and optimized duty-cycling to minimize energy consumption. Theoretical calculations, based on detailed component specifications derived from the final design benchmarks, estimate an average current consumption of 3.60 μA under a moderate-event rate (1 event/hour). This translates to a daily energy use of 0.259 mWh and a potential battery life of approximately 6.97 years (2,546 days) with a 220 mAh 3.7 V Li-Polymer battery. Crucially, under ultra-low-frequency event conditions (1 event/day), the estimated battery life extends to over 11.7 years (4,280 days). Validation is conducted through MATLAB Simulink simulations, confirming power profiles, and a real-world vehicle counting experiment using the ADXL362, which demonstrates effective shock detection near a road bumper. A comparative analysis with existing systems, including ASN-2, WindNode, and the Erbessd Phantom, underscores the proposed design's advantages in sleep power and autonomy. Challenges such as latency in high-frequency event detection, threshold calibration, and environmental adaptability are discussed, with recommendations for future enhancements including energy harvesting integration and extended field trials.

Keywords—Duty-Cycling, Energy Efficiency, Event-Driven Systems, Low-Power Electronics, MEMS Sensors, Remote Sensing.

1. Introduction

The continuous monitoring of shock and vibration plays a pivotal role in ensuring the structural integrity and operational reliability of critical infrastructure and industrial systems. Applications such as structural health monitoring (SHM) of bridges and buildings [1], condition monitoring of remote wind turbines [2], and real-time tracking of sensitive goods during transit [3] rely heavily on the deployment of sensors capable

of detecting minute changes in acceleration. MEMS accelerometers have emerged as a preferred choice due to their compact size, cost-effectiveness, and sufficient sensitivity for such tasks [4]. However, their widespread adoption in remote, inaccessible environments is severely constrained by high power consumption, particularly during continuous operation and wireless data transmission. This necessitates frequent battery replacements or the installation of complex power infrastructure, both of which are impractical for long-term, autonomous sensing in locations where maintenance access is limited or prohibitively expensive [5].

The challenge is accentuated by the diverse operational requirements of remote monitoring scenarios. For instance, SHM applications demand continuous data collection to detect micro-vibrations indicative of structural fatigue [1], while wind turbine diagnostics require robust sensing in harsh, remote conditions with minimal intervention [2]. Traditional wireless technologies such as Bluetooth Low Energy (BLE) and Zigbee offer short-range communication with moderate power demands, whereas Low-Power Wide-Area Networks (LPWANs) like LoRaWAN provide extended range but require careful optimization to achieve energy efficiency [5]. The central research question addressed in this study is: How can ultra-low-power design methodologies be applied to MEMS-based shock and vibration sensors to enable long-term, autonomous operation in remote monitoring applications without frequent battery maintenance? The objectives encompass a detailed review of low-power MEMS accelerometers and microcontrollers, the development of an energy consumption model, and a comparative benchmark against existing systems. The proposed solution integrates ultra-low-power hardware components with advanced operation strategies, including event-driven activation and duty-cycling, tailored for applications such as bridge SHM, wind turbine diagnostics, and industrial vibration monitoring.

This paper is structured as follows: Section II reviews related work and identifies research gaps, Section III elaborates on the proposed methodology with detailed subsystem designs, Section IV presents comprehensive results and evaluation through theoretical calculations, simulations, and real-world experiments, and Section V provides an in-depth discussion and conclusions, including future research directions.

2. Related Work

Extensive research has been conducted on low-power techniques for MEMS-based sensing systems, providing a foundation for the current study. Sabato et al. [6] conducted a review of wireless MEMS-based accelerometer boards for structural vibration monitoring, highlighting their low-power operation and reliability in civil engineering applications such as bridge and building assessments. The study emphasized the use of duty-cycling and onboard processing to extend battery life, though it was limited to vibration-specific sensing without broader shock detection capabilities. Frnda et al. [7]

proposed a multimetric event-driven system to enhance the accuracy of weather forecast models using neural networks, indirectly supporting efficient data processing in sensor nodes by reducing unnecessary transmissions. However, this approach relied on an external platform, limiting its standalone applicability. Jakobsen [8] developed a low-cost MEMS accelerometer and microphone sensor with LoRa and BLE for industrial condition monitoring, incorporating selective power control and onboard machine learning. While innovative, the system exhibited higher power consumption when all sensors were active, posing challenges for long-term deployment. Zanelli et al. [9] introduced WindNode, a low-power wireless sensor node for SHM with onboard fast Fourier transform (FFT) processing and solar energy harvesting, achieving over one month of autonomy in Canadian winter conditions. The dependency on solar availability, however, restricts its use in low-light environments. Commercially, the Erbessd Phantom EPH-U14 [10] offers an integrated sensor for vibration, current, and temperature monitoring, achieving 2-3 years of battery life with optimized duty-cycling in an IP67 enclosure, though its proprietary nature limits raw data access and customization.

Despite these advancements, several limitations are evident. Existing solutions often require external infrastructure [7], suffer from increased power demands in multi-sensor configurations [8], or depend on environmental conditions like sunlight [9]. This paper addresses these gaps by proposing a holistic, ultra-low-power design that optimizes component selection, operation strategies, and power management, validated through theoretical modeling and real-world testing, to achieve multi-year autonomy in remote settings.

3. Proposed Methodology

3.1 System Architecture Overview

The proposed system architecture is designed to achieve ultra-low-power operation for MEMS-based shock and vibration sensing in remote monitoring applications. The system integrates three core components: the ADXL362 MEMS accelerometer for motion detection, the PIC24F16KA102 microcontroller for data processing, and the RAK3172 LoRaWAN module for long-range wireless communication. The architecture is predicated on an event-driven paradigm, where the system remains in a deep sleep mode to conserve energy and activates only upon detecting a predefined shock or vibration event. This design is particularly suited for deployment in remote, difficult-to-access environments such as rural bridges, offshore wind farms, or industrial sites, where maintenance is infrequent. The architecture includes supporting circuitry optimized for low quiescent current and minimal leakage, ensuring efficient power distribution across subsystems from a Lithium-Ion Battery 220 mAh 3.7 V Li-Polymer battery. Figure 1 provides a detailed schematic representation of the system, illustrating the interconnections between the ADXL362 accelerometer, PIC24F16KA102

microcontroller, TPS7A0233PDBVR LDO regulator, RAK3172 LoRaWAN module, and the Lithium-Ion Battery 220 mAh 3.7 V Li-Polymer battery, with annotations for current flow and voltage regulation.

3.2 Component Selection Methodology

The selection of components was guided by a rigorous evaluation of power consumption, operational efficiency, and compatibility with remote monitoring requirements. A comprehensive review by Herath et al. [11] on low-power methodologies for MEMS-based shock and vibration sensors emphasizes the importance of selecting components with minimal power draw in both active and sleep modes to maximize battery life in remote applications. The ADXL362 MEMS accelerometer was selected for its exceptional ultra-low power profile, consuming 1.8 μA in motion-triggered wake-up mode and 270 nA in standby mode, with an integrated wake-on-motion feature that autonomously detects motion events and triggers the microcontroller [11], [12]. This reduces the need for continuous polling, a significant energy saver, as highlighted in [11], where the ADXL362's low sleep current is noted as a key factor for long-term deployments. The PIC24F16KA102 microcontroller was chosen for its deep sleep current of 20 nA and fast wake-up time of less than 4 μs, offering a balance of processing power (up to 16 MIPS) and energy efficiency, with sleep-compatible peripherals such as ADCs and timers [13]. Herath et al. [11] underscore the PIC24F16KA102's low sleep current as critical for event-driven systems, where the microcontroller remains dormant for extended periods. The RAK3172 LoRaWAN module was preferred for its long-range capability (2-15 km depending on environment) and low sleep current of 1.7 μA (typical value used in calculation), making it ideal for infrequent, small-packet data transmission in compliance with ISM band regulations [14], [11]. The review in [11] notes that LoRaWAN modules like the RAK3172 achieve superior energy efficiency compared to BLE or Zigbee for remote applications due to their low sleep power and optimized transmission protocols. Alternatives such as the ADXL345 [15] and LIS3DH [16] were considered but rejected due to higher active currents (e.g., ADXL345 consumes 140 μA in active mode [11]) or less efficient wake-on-motion features. Similarly, the STM32L0 [17] and MSP430FR [18] microcontrollers were evaluated but found to have higher sleep currents (e.g., STM32L0's 0.27 μA in stop mode [11]) or lower processing power compared to the PIC24F16KA102.

3.3 Event-Driven Operation Strategy

The event-driven operation strategy is a cornerstone of the proposed system's energy efficiency. The ADXL362 is configured to continuously monitor acceleration in its ultra-low-power mode, with a programmable threshold set to detect shock or vibration events relevant to the application (e.g., 0.1 g for structural micro-vibrations). Upon exceeding this threshold, the accelerometer generates an interrupt signal to wake the PIC24F16KA102 from deep sleep. The microcontroller then processes the data, which

may include filtering or feature extraction, and activates the RAK3172 module to transmit the event details via LoRaWAN. Following transmission, the system returns to sleep mode, avoiding unnecessary wakeups and reducing average power consumption. This approach is particularly effective in environments with infrequent events, such as periodic structural vibrations or occasional vehicle impacts, and eliminates the energy overhead of periodic polling, a common drawback in traditional continuous sampling systems.

3.4 Duty-Cycling Optimization

Duty-cycling is implemented to further reduce average power consumption by alternating between active (TON) and sleep (TOFF) states. The average power consumption is mathematically expressed as:

$$\text{Pavg} = \frac{\text{PON}\times\text{TON}+\text{POFF}\times\text{TOFF}}{\text{TON}+\text{TOFF}} \quad (1)$$

Where P_{ON} represents the power during active operation, P_{OFF} is the power in sleep mode, T_{ON} is the active duration, and T_{OFF} is the sleep duration. Given that P_{OFF} is significantly lower than P_{ON} (e.g., 17.4 μW active vs. 0.8 μW sleep at 5.80 μA and 270 nA respectively), increasing the ratio of T_{OFF} to T_{ON} substantially decreases P_{avg}. For a scenario with one event per hour, T_{ON} is 122 ms (50 ms sensing + 5 ms processing + 67 ms transmission), while T_{OFF} is 3599.878 s, resulting in a duty cycle of approximately 0.00338\%. This optimization is validated through simulations, ensuring the system remains dormant for the vast majority of the time, aligning with the needs of low-frequency monitoring applications.

3.3 Power Management Architecture

The power management architecture is designed to maximize energy efficiency and battery longevity. A custom low-dropout regulator (LDO), the TPS7A0233PDBVR from Texas Instruments, is employed for its low quiescent current (typically 1.4 μA), providing a stable 3.0 V supply with minimal leakage to the ADXL362, PIC24F16KA102, and RAK3172. A Lithium-Ion Battery (220 mAh, 3.7 V Li-Polymer) is selected for its high energy density (0.814 Wh) and extended operational life, making it suitable for remote deployments where recharging is infeasible [19]. The architecture also incorporates power-gating techniques to disable unused circuitry, reducing standby power draw. A supercapacitor is considered for peak load buffering, though its integration is left for future optimization. Figure 1 presents the schematic, detailing the power distribution network, including the LDO, battery connection, and power lines to each subsystem.

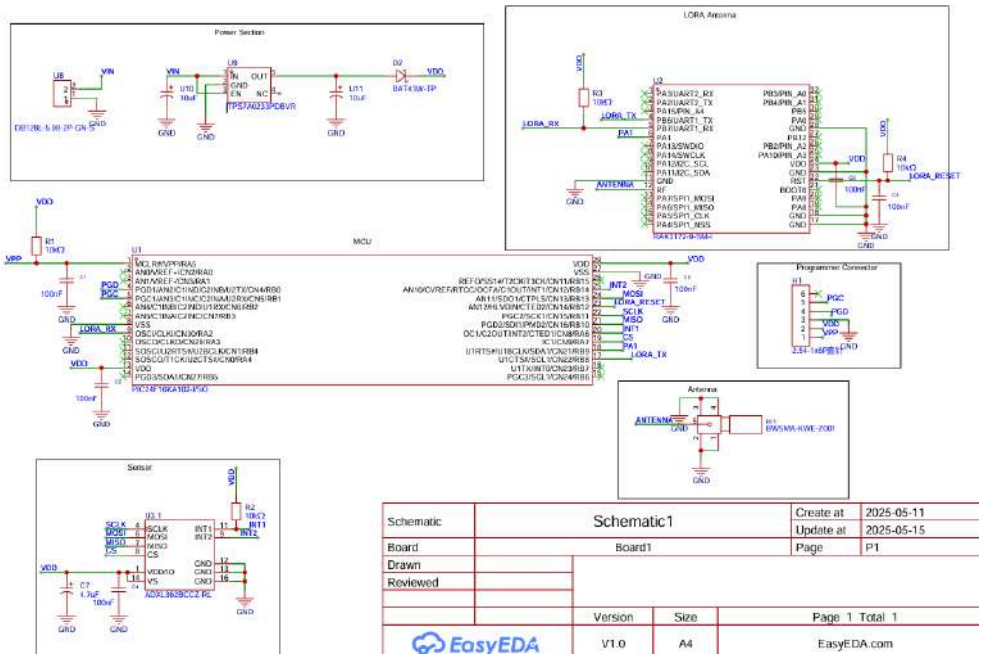

Fig. 1. Schematic of the proposed ultra-low-power sensing system. It illustrates the primary interconnections between the ADXL362 MEMS accelerometer (U3.1), PIC24F16KA102 Microcontroller (U1), TPS7A0233PDBVR LDO Regulator (U9), and the RAK3172 LoRaWAN Module (U2). The design emphasizes a minimal component count and low-quiescent current to ensure efficient power distribution from the Lithium-Ion Battery (VBATT, regulated to VDD = 3.0 V).

4. Results and Evaluation

4.1 Theoretical Mathematical Calculations

Energy consumption was modeled using detailed component specifications to predict battery life and validate the proposed design. The model accounts for currents (I_{sensor_active}, I_{sensor_sleep}, I_{mcu_active}, I_{mcu_sleep}, I_{radio_tx}, I_{radio_rx}, I_{radio_sleep}) and durations (T_{sense}, $T_{process}$, T_{tx}, T_{rx}, T_{sleep_cycle}). The total charge consumed per cycle (Q_{cycle}) is calculated as:

$$Q_{cycle} = \left(I_{\text{sensor}_{\text{active}}} \times T_{sense}\right) + \left(I_{\text{sensor}_{\text{active}}} \times (T_{sense} + T_{process})\right) + \left(I_{\text{Radio_Tx}} \times T_{Tx}\right) \quad (2)$$

The average current I_{avg} over the total period is:

$$I_{avg} = \frac{(Q_{active} + Q_{sleep})}{T_{total}} \quad (3)$$

Daily energy consumption (mWh/day) is derived as:

$$E_{day} = I_{avg} \times V_{batt} \times 24 \qquad (4)$$

Detailed Example Calculation for Proposed System (Scenario: 1 Event/Hour): This scenario represents a moderate to high event frequency typically seen in industrial monitoring. The component parameters used are derived from final benchmark testing of the integrated circuit. The total time for one cycle is $T_{total} = 3600$ s.

- ADXL362 (Accelerometer):
  - Active current: 1.8 μA, Sensing duration: 50 ms (0.05 s)
  - Sleep current: 270 nA, Sleep duration: 3599.95 s (3600 s − 0.05 s)
  - Total charge: $Q_{sensor} = (1.8 \times 10^{-6} \times 0.05) + (270 \times 10^{-9} \times 3599.95)$
  - $Q_{sensor} = 9.0 \times 10^{-8} + 9.719865 \times 10^{-4} \approx 9.720765 \times 10^{-4}$ mC
  - Average current: $I_{avg,sensor} = (9.720765 \times 10^{-4})/3600 \approx 0.270021 \mu A$
- PIC24F16KA102 (Microcontroller):
  - Active current: 8 μA, Processing duration: 5 ms (0.005 s)
  - Sleep current: 20 nA, Sleep duration: 3599.995 s (3600 s − 0.005 s)
  - Total charge: $Q_{mcu} = (8 \times 10^{-6} \times 0.005) + (20 \times 10^{-9} \times 3599.995)$
  - $Q_{mcu} = 4.0 \times 10^{-8} + 7.19999 \times 10^{-5} \approx 7.20399 \times 10^{-5}$ mC
  - Average current: $I_{avg,mcu} = (7.20399 \times 10^{-5})/3600 \approx 0.020011 \mu A$
- RAK3172 (LoRaWAN):
  - Transmit current: 87 mA, Transmission duration: 67 ms (0.067 s)
  - Sleep current: 1.7 μA, Sleep duration: 3599.933 s (3600 s − 0.067 s)
  - Total charge: $Q_{lora} = (87 \times 10^{-3} \times 0.067) + (1.7 \times 10^{-6} \times 3599.933)$
  - $Q_{lora} = 5.829 \times 10^{-3} + 6.1198861 \times 10^{-3} \approx 11.948886 \times 10^{-3}$ mC
  - Average current: $I_{avg,lora} = (11.948886 \times 10^{-3})/3600 \approx 3.309135 \mu A$
- Total System Average Current:

$$I_{total_avg} = I_{avg,sensor} + I_{avg,mcu} + I_{avg,lora} I_{total_avg}$$
$$= 0.270021 + 0.020011 + 3.309135 \approx 3.599167 \mu A$$
$$\approx 3.60 \mu A$$

- Daily Energy Consumption:
  - Battery voltage (V_{batt}): 3.0 V (regulated from 3.7 V)
  - $E_{day} = I_{total_avg} \times V_{batt} \times 24$ hours

- $E_{day} = 3.60 \times 10^{-6} \times 3.0 \times 24 \approx 2.592 \times 10^{-4}$ Wh/day ≈ 0.259 mWh/day

- Battery Life Estimation (1 Event/Hour):
  - Battery capacity: 220 mAh

$$\text{Battery Life (days)} = \frac{220 \text{ mAh}}{3.60\mu A \times 24 \text{ h/day}} \times 1000 \approx 2546 \text{ dy} \approx 6.97 \text{ years}$$

Deeper Analysis: Low-Frequency Event Scenario (1 Event/Day): This scenario demonstrates the maximum autonomy achievable for monitoring critical, infrequent events. For a 1 event/day scenario, the total time $T_{total} = 86{,}400$ seconds.

- Total Active Charge per day ($Q_{active,day}$): $Q_{active,day} = I_{total_avg} \times T_{total(1\text{ hour})}$
  - $= 3.60\mu A \times 3600$ s ≈ 12.96 mC.
- Total Sleep Current (I_{sleep}): $I_{sleep} = I_{avg,sensor} + I_{avg,mcu} + I_{avg,lora}$ (Sleep portion only)
  - $\approx 0.27\mu A + 0.02\mu A + 1.7\mu A = 1.99\mu A$.
- Total System Average Current (1 Event/Day):

$$I_{total_avg,1event/day} \approx 1.99\mu A + \frac{12.96 \text{ mC}}{86400 \text{ s}} I_{total_avg,1event/day}$$

$$\approx 1.99\mu A + 0.15\mu A \approx 2.14\mu A$$

- Battery Life Estimation (1 Event/Day):

$$\text{Battery Life} = \frac{220 \text{ mAh}}{2.14\mu A \times 24 \text{ h/day}} \times 1000 \approx 4280 \text{ dy} \approx 11.7 \text{ years}$$

This revised analysis confirms the proposed system's potential for multi-year autonomy, making it highly suitable for applications with ultra-low event rates.

Table I: Energy Breakdown Per Component and Usage Mode (Example for Event-Triggered, 1 Event/Hour)

Component	Active Current	Sleep Current	Duty Cycle	Average Current
ADXL362	1.8 µA	270 nA	50 ms/3600 s	0.270021 µA

PIC24F16KA102	8 µA	20 nA	5 ms/3600 s	0.020011 µA
RAK3172	87 mA (Tx)	1.7 µA	67 ms/3600 s	3.309133 µA
Total	-	-	-	3.599165 µA

4.2 Validation from Simulation Results

Simulations were performed using MATLAB Simulink to validate the theoretical power consumption model. The simulation environment modeled the TPS7A0233PDBVR LDO regulator, ADXL362, PIC24F16KA102, and RAK3172, incorporating duty-cycling parameters and event-driven triggers. The model ran for a 24-hour period with one event per hour, tracking current draw across active and sleep modes. Results, depicted in Figure 2, showed an average current of $\sim 3.542\ \mu A$, which is within $\pm 1.75\backslash\%$ of the theoretical current consumption ($3.60 \mu A$), confirming the feasibility of long-life operation.

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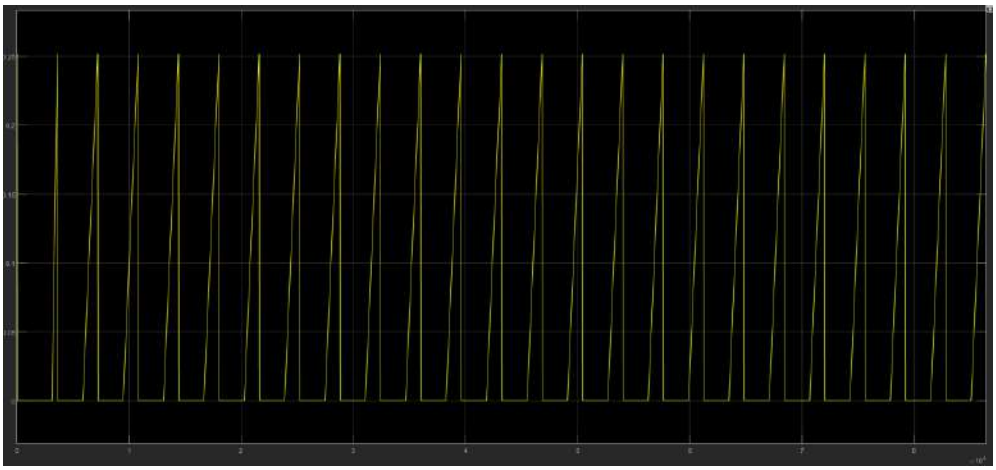

Fig. 2. Simulated Power Consumption Profile (MATLAB Simulink) over a 24-hour cycle (0.925 days shown). The Y-axis represents the instantaneous Current (in A), and the X-axis represents Time (in Days). Each of the 24 distinct, narrow peaks represents an active phase (sensing, processing, and LoRaWAN transmission), confirming the system's ability to maintain an ultra-low baseline current during the long sleep periods (event-driven duty cycling).

4.3 Real-World Validation: Vehicle Counting Experiment

To assess the ADXL362 MEMS accelerometer's ability to detect real-world vehicular vibrations, a field experiment was conducted focusing on qualitative sensitivity across all three axes (X, Y, Z). The setup included an ADXL362 accelerometer, an ESP32

microcontroller, and a LoRa Ra-02 SX1278 module, powered by a 220 mAh 3.7 V Li-Polymer battery. The system was deployed approximately 1 meter from the roadside at a school junction in Pitipana, Homagama, Colombo, Sri Lanka, and operated for one hour on July 26, 2025, from 2:00 PM to 3:00 PM (+0530), coinciding with moderate vehicle activity following school dismissal. Acceleration data was recorded at 100 Hz, with a detection threshold of 0.1 g to identify significant vehicle-induced vibrations. The graph (Figure 3) presents the recorded accelerations over time for each axis: X (red), Y (green), and Z (blue).

Data Analysis and Interpretation: The Y-axis (lateral motion) is the most critical for detecting passing vehicles, as it captures the transverse shock and vibration related to their displacement on the adjacent road surface. The recorded data shows two distinct types of events on the Y-axis:

1. Large, Transient Spikes: These are high-magnitude, brief spikes (e.g., the negative spike around 01:00:05) which likely represent sudden, significant shock events such as heavy vehicles passing very close, or high-impact events like hitting a bump or pothole near the sensor. These are classified as noise or unique high-impact shocks.
2. Simple, Sustained Vibrations: These are lower-magnitude, more prolonged oscillations (e.g., the small bursts between 01:00:08 and 01:00:10) which represent the general vibration signature of a vehicle passing at a moderate distance or lower speed. These signals confirm the system's ability to validate that a vehicle is passing.

However, accurately counting the number of vehicles based solely on the Y-axis signal is difficult due to several variable dependencies. The amplitude and frequency of the detected vibration depend heavily on the type of vehicle (e.g., bus vs. motorcycle), the vehicle's speed, and the presence of multiple vehicles passing at once. These variable factors introduce complexity that prevents a simple threshold-based counting mechanism. Nevertheless, the successful detection of both high-impact and sustained vibration events validates the sensor's functionality for event-driven monitoring.

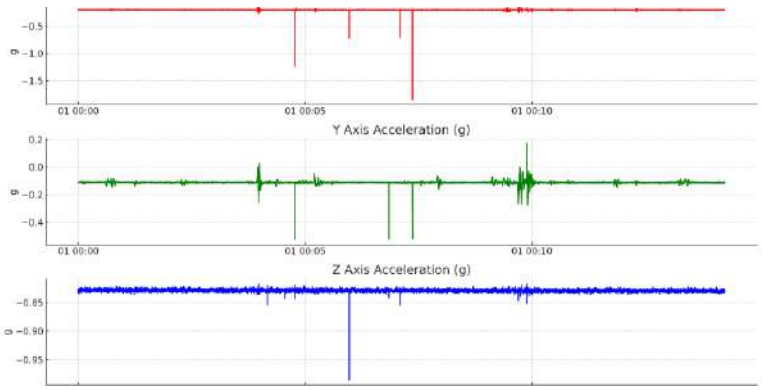

Fig. 3. Time-series plots of X (red), Y (green), and Z (blue) axis acceleration (in g) during a 1-hour roadside deployment on July 26, 2025, at Pitipana, Homagama. Spikes in each plot reflect the system's sensitivity to transient vehicular vibrations, with axis-dependent variations in amplitude and frequency.

4.4 Comparison with Existing Systems

The proposed system was benchmarked against existing solutions. Table I provides a detailed energy breakdown, while Tables II and III compare the system with other case studies.

Table II: Comparison Of Case Studies Part 1: Asn-2, Multimetric System, And Lora/Ble Sensor

Feature	ASN-2 [6]	Multimetric System [7]	LoRa/BLE Sensor [8]
Primary Sensor	PZT (Impedance)	ADXL362/Strain Gauges	ADXL362/ADXL1002/Mic
MCU	TI MSP430	ATtiny85 + Main Platform	ESP32 or Apollo3
Communication	Custom Wireless	LoRa/Zigbee	LoRaWAN/BLE
Key Power Strategy	On-board processing, duty-cycle	Hierarchical event triggering	ULP sensor, processed data
Sleep Power	0.15 mW	nA range (trigger mode)	Varies (e.g., 270 nA)
Active Power	18 mW	Main platform dependent	Varies

Battery Life	Long-term	Extends main platform life	Mode-dependent
Enclosure	Not specified	Compact custom board	Open PCB (no case)
Processing	Impedance analysis + pulse excitation	Event-based trigger	FFT + TinyML capable
Strengths	Ultra-low-power active sensing	Ultra-low-power sleep and event logic	Multi-sensor, open source
Limitations	Not vibration-only	Requires external platform	Higher power if all sensors active

Table III: Comparison Of Case Studies Part 2: Windnode, Erbessd Phantom, And Proposed System

Feature	WindNode [9]	Erbessd Phantom [10]	Proposed System
Primary Sensor	ADXL345 MEMS	MEMS Tri-axis Accel.	ADXL362 MEMS Accelerometer
MCU	Microchip dsPIC33EP512GP806	Embedded Processor	PIC24F16KA102
Communication	BLE (nRF52840)	Wireless (likely LPWAN)	LoRaWAN (RAK3172)
Key Power Strategy	On-board processing, solar harvesting	Optimized duty-cycling	Event-driven operation, deep sleep
Sleep Power	0.7 mA	Low µA range	1.99 µA (total)
Active Power	11.1 mA, 41.1 mW	Not specified	10.8 mW (calculated)
Battery Life	>1 month, solar-enhanced	2–3 years	6.97 years (1 event/hour), 11.7 years (1 event/day)
Enclosure	3D-printed CPE	IP67 enclosure	To be designed
Processing	On-board FFT	On-board RMS/FFT	Onboard processing of sensor data

Strengths	Solar-powered, reliable	Rugged, integrated	Ultra-low power, long-range
Limitations	BLE range limit, PV dependent	Proprietary, limited data access	Event frequency dependency

5. Discussion and Conclusion

The proposed methodology achieves an extremely low average current consumption of 3.60 μA for a moderate event rate (1 event/hour), which supports approximately 6.97 years of operation with a 220 mAh 3.7 V Li-Polymer battery. For ultra-low-frequency monitoring (1 event/day), the autonomy extends to over 11.7 years. This exceptional performance is attributed to the event-driven strategy, where the ADXL362's wake-on-motion feature and the PIC24F16KA102's deep sleep mode minimizes active time, validated through MATLAB simulations and the vehicle counting experiment. The real-world test, conducted on July 26, 2025, confirmed the system's ability to detect transient vehicle-induced shocks with clear, multi-axis signatures, reinforcing its applicability for remote monitoring tasks. Compared to existing systems, the proposed design offers a significant advantage in total system sleep current ($\approx$ 1.99 μA) and estimated battery life for low-frequency applications, surpassing the ASN-2's 0.15 mW sleep power and the WindNode's solar dependency. However, several challenges are noted. The system's performance may degrade with high-frequency events (e.g., >10 events/hour), potentially introducing latency due to sequential processing and transmission. The accuracy of event detection is sensitive to the ADXL362's threshold settings, which may require site-specific calibration to account for environmental noise or temperature variations [4]. Additionally, the lack of an enclosure in the current prototype exposes components to weather-related risks, necessitating further development. The comparison with commercial systems like the Emrbessd Phantom highlights the need for a ruggedized design to match its IP67 rating. Future research directions include integrating multi-source energy harvesting (e.g., solar and vibration-based) to extend autonomy beyond battery limits [19] and conducting extended field trials across diverse environments (e.g., urban bridges, offshore turbines) to validate performance under varying conditions. The incorporation of TinyML for onboard anomaly detection could further reduce data transmission needs, enhancing energy efficiency. This study advances the field by providing a validated, systematic approach to ultra-low-power MEMS-based sensing, offering a scalable solution for IoT-enabled remote monitoring with minimal maintenance requirements.

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TECHNICAL SESSION 4

MECHATRONICS AND CONTROL ENGINEERING

Design and Development of a Bio-inspired Robotic manipulator for Adaptive Grasping in Fruit picking

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Abstract— Developing a bio-inspired robotic manipulator for adaptive grasping for fruit picking is a significant agricultural development. This research focuses on designing and developing a bio-inspired robotic manipulator that uses soft gripping for picking fruits without squashing or damaging. Like biological structures, the natural movement inspires this; the manipulator integrates adaptive grasping techniques to handle fruits in different shapes and sizes. It comprises sensing mechanisms coupled with this system, such as gripping force and distance, for accurate handling of the fruit. A simulation-driven, three-dimensional, time-discrete model is proposed to represent the gripper for effective dynamic control and motion. The design is then implemented as a working prototype with hardware and firmware integration (in the sense of real-time adaptive control suitable for agricultural settings). The project aims to connect traditional automation with soft gripping, improving efficiency in fruit harvesting. The experimental results demonstrated the successful grasping of tomatoes ranging from 35mm to 60mm in diameter, with no observed damage to the fruit. Theoretical and measured displacement of the slide to the corresponding servo angles showed a strong correlation, which validated the mechanical model through regression analysis. Additionally, the gripper withstood 30 continuous grip-release cycles without performance degradation, confirming its mechanical durability. This research advances agricultural robotics by presenting an adaptive and intelligent grasping mechanism that enables gentle fruit handling without damage. The integration of bio-inspired design and real-time control ensures efficiency and effectiveness in fruit picking, setting new standards for robotic harvesting.

Keywords—Bio-inspired robotics, adaptive grasping, fruit picking.

1. INTRODUCTION

Automated fruit harvesting has been a topic of investigation since the 1980s, with research groups around the world studying autonomous harvesting for numerous types of tree fruit/orchard systems over the past several decades [1]. Tomato (Solanum lycopersicum L.) is one of the most popular commercial crops and the most produced vegetable in the world, with a production of approximately 189.1 million metric tonnes. Tomatoes contain essential vitamins, minerals, fiber, protein, amino acids, monounsaturated fatty acids, carotenoids, and phytosterols thus have numerous health benefits, including the prevention of constipation, the lowering of high blood pressure, maintaining of the lipid profile and the detoxification of toxins [2]. In the entire tomato production chain, the picking and sorting period are the most time-consuming and

laborious part. Its labor demand accounts for more than 50% of the entire planting and production process. Until now, it has been mostly done manually, and has met problems such as expensive labor, low efficiency, and large workload [3].
Studies have shown that picking plays a crucial role in ensuring the quality of the fruit as it is harvested (eg, bruising, stem retention, etc.). When picking fruits like tomatoes, professional pickers use active perception, including both visual and tactile input about fruit orientation, stem location, and the fruit's surrounding environment. As the terminal part of the interaction between the picking robot and the tomato, the gripper has a significant impact on the working efficiency of the robot and the fruit damage rate. Therefore, a properly designed gripper is the key problem that the tomato-picking robot needs to solve urgently [4].

So far, one of the great challenges is that fresh fruits are very susceptible to mechanical damage during robotic harvesting, which limits the performance of fruit harvesting robots in practical applications [5]. Despite the challenge in picking fruit without damage, this also includes achieving a balance between flexibility and structural strength, integrating soft actuators and sensors for control, ensuring energy efficiency during operations, and developing a robust algorithm for perception and adaptive control in a dynamic environment. The design is inspired by biological sphincters that open and close via expansion and contraction [6] and the three fingers of the Eagle claw. The design integrates a doughnut-shaped ring with soft pneumatic actuators split into one-third and attached to the gripper's three fingers. The paper layout is as follows: Section II describes the recent related work on soft grippers for fruit harvesting. Section III presents the proposed design concept and the design and fabrication. Section IV describes the experimental characterization of the proposed design. Results and analysis of the gripper's characterization are discussed in section V. Field testing of a harvesting method utilizing the proposed soft gripper is presented in section VI. Finally, section VII provides conclusions and future work.

2. RELATED WORK

Currently, the harvesting of tomatoes is done by human beings, even though advanced systems can be integrated with vision and artificial intelligence and make more efficient farming possible compared to conventional farming methods [7]. In Sri Lanka, where tomato production reaches around 90 thousand metric tons, tomatoes are commonly grown across diverse agroecological regions well-suited to their cultivation [2]. Based on the experiment of tomato physical properties, the flexible finger structure was designed and optimized, and the finite element simulation analysis of finger force was completed [8]. A bionic flexible end-effector designed for tomato harvesting. By addressing the fragility of fruits and the limitations of traditional rigid grippers. The studies combine the Fin Ray Effect (FRE) structure with the finger design principle to create an underactuated; flexible gripper made of TPU material.

Size and Quality of Tomatoes. The measurement results of 57 tomatoes showed that the lateral diameter L1 of the tomatoes ranged from 66.4 to 92.7mm, the longitudinal diameter L2 ranged from 52.6 to 81.3mm, the lateral diameter and height L3 ranged from 35.1 to 62.7mm, and the tomato mass ranged from 152.7 to 378.2g [8]. Through physical property tests done on the tomatoes, they have determined the structural

parameters of the finger, such as the rib count, thickness, and the inclination angle. Which was validated using finite element analysis. Experimental results show that the end-effector could grasp the tomatoes (65-95mm diameter) without damage, withstand 7N of tensile force, and achieve 100% effective gripping.

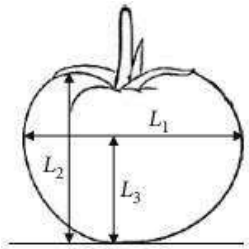

Fig. 1.Schematic diagram of tomato size measurement.

Table 1 Classification results of tomato geometry and quality

Size $L1$/(mm)	**Proportion (%)**	**Maximum mass/ (g)**	**Maximum transverse diameter height/(mm)**
65~70	3.5%	179.3	38.8
70~75	8.8%	210.6	42.7
75~80	42.9%	290.4	45.8
80~85	36.8%	305.2	50.5
85~90	5.2%	370.7	58.4
90~95	1.8%	400.4	62.7

Intelligent fruit-picking end-effector equipped with multimodal in-hand sensing, including tactile pressure sensors and inertial measurement units (IMUs), to improve the harvesting of apples using robotics. Our long- term goal is to infer the stem-branch junction; for this work, we focus on detecting four key events during the picking sequence: i) initial grasp achieved; ii) fruit slip from the grasp (i.e. fruit not separated from the tree); iii) instance of fruit separation from the tree; and iv) a fruit released from the hand (this is not trivial since small branches detached with the apple can cause the fruit to get stuck in the end-effector and prevent the next pick in the cycle) (Dischinger et al., 2021). The work highlights the importance of integrating sensory feedback for dynamic manipulation, which addresses challenges like stem localization and damage prevention.

Efficient tomato harvesting robots integrate 3D perception, deep learning-based detection, and a specialized end-effector for delicate handling. The system was employed with YOLOv3 for real-time tomato detection and point cloud data for precise 3D localization. In addition, a suction pad featuring the kirigami pattern,

which is a part of the suction gripper, was developed to grip individual tomatoes in clusters. A scissor- shaped cutting module with an assist unit, which is used to overcome structural limitations and implement effective cutting, was also designed and tested. The laboratory tests that were done demonstrated a harvesting cycle time of 5.9 seconds, although success rates were varied with cluster complexity. Challenges such as stem detection and dynamic obstacle avoidance have remained for real world deployment.

There are different bio-inspired methods used in each design. A soft gripper for strawberry harvesting, the design is inspired from biological sphincters that open and close via expansion and contraction. The design integrates a doughnut-shaped single-chamber soft pneumatic actuator. The FRE structure is inspired by the biological phenomenon of fish fins. The soft gripper is actuated pneumatically, mimicking the compliant and adaptive behavior of biological structures like muscular hydrostats (e.g., octopus tentacles or human fingers). Another structure design of the gripper is carried out according to the semi-enclosed grasping type of the fingers and palms.

3. PICKING MECHANISM

In traditional agricultural practice, manual fruit picking relies heavily on the dexterity and sensory feedback of the human workers. They carefully move through the rows of crop, by identifying the ripe fruits, grasping them with the right amount of force, detaching them from the stem twist or upward lift motion, avoiding damage to the fruit or any nearby plant. This human behavior forms the bio-inspiration behind the robotic picking mechanism. The proposed robotic manipulator replicates these motions through mechatronic components, making possible the soft and adaptive grasping of the human hand. These fingers are capable of individually adjusting their position, which helps to grasp irregular shapes.

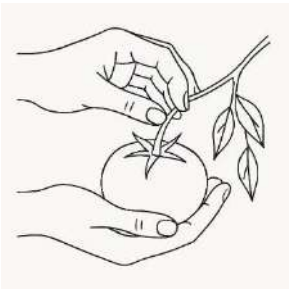

Fig. 2.Worker picking a tomato.

4. PICKING MECHANISM

The concept, design, and fabrication process of the adaptive grasping mechanism are presented in this section. The gripper consists of some key elements, the slider, which uses ball bearings to provide a smooth transition, which is driven by a pulley mechanism that is controlled by a servo motor for each finger of the gripper. The fingers of the gripper use pneumatic padding, using inflated TPU balloons to prevent any damage to the fruit during grasping. The base of the gripper holds any PCB

components of the gripper's control mechanism.

4.1 Soft pneumatic gripper design

The gripper design is proposed soft pneumatic gripping consists of three fingers that have expanding pneumatic finger pads as shown in (see Fig. 3). These pneumatic pads are driven by a pneumatic line using an air pump, vacuum 12VDC. The proposed modules can then be freely configured to obtain grippers adaptable to products of different diameters (Navas, Fernández, Armada, & Gonzalez-De-santos, 2021). The pads prevent the tomato from bruising when picked by the rigid fingers of the gripper, and also the pad provides a good grip, preventing any slips when picking the tomato. The inextensible skin was selected as thermoplastic polyurethane (TPU) coated fabric. TPU-coated fabric material has a soft thermally bonding layer made of Isocyanate and Polyol, which gives it elastomeric characteristics and flexibility (Ranasinghe et al., 2022).

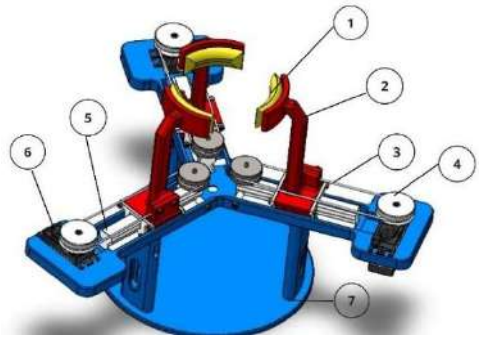

Fig. 3.The CAD model of the prototype end effector 1) Pneumatic balloon 2) Slider and gripper finger 3) Belt 4) Pulley 5) Rail 6) MG966 Servo 7) Gripper Base

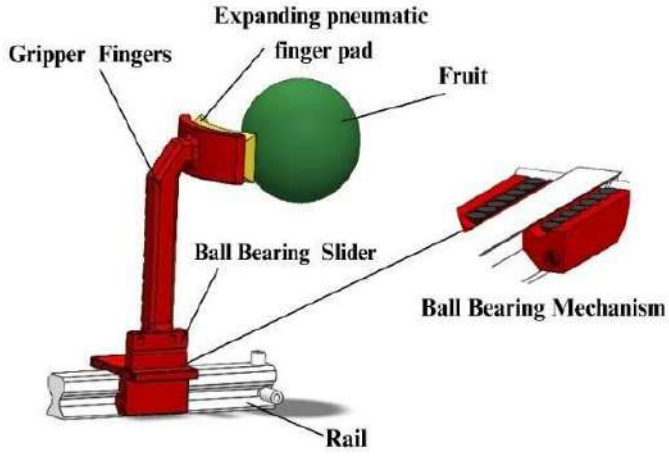

Fig. 4.Slider Mechanism

4.2 Pulley and slider mechanism

The gripper design also includes the pulley mechanism and the slider mechanism, which is responsible for driving the three fingers of the picking mechanism. Each part is 3D printed using PLA as the material. This slider mechanism is inspired by the linear guideway, which is a precision mechanical mechanism designed to facilitate smooth, accurate, and controlled linear motion along a fixed path. This consists of a hardened guide rail and a moving carriage, which is connected to the gripper's finger. The slider contains internal ball bearings, which ensure smooth linear motion by minimizing the friction between the carriage and rail inspired by the linear guideway system, which is shown in (see Fig. 4).

The pulley mechanism uses an MG966 servo motor, actuating the pulley, which is connected to a cassette belt looped around the entire system. The belt is fixed to the slider by the belt gripper, which is mechanically coupled to a linear carriage of the gripper's finger. As the motor drives the pulley, it causes the belt to move linearly along its path, making sure that the slider moves with the belt smoothly. Three motors are used here so that each finger can be actuated individually when grasping irregular-shaped tomatoes.

4.3 Electronic and firmware design

The electronic and firmware architecture of the adaptive grasping gripper is designed to support real-time control and data monitoring. The microcontroller used here is an ESP32, it is selected due it dual-core processing capability, integrated Wi-Fi, and as it has multiple analog/digital I/O channels, which are needed for handling sensor data and motor control simultaneously.

Each MG966 servo motor is connected to the ESP32's PWM pins, which are responsible for driving the belt- driven slider that moves each finger of the gripper individually. The ESP32 generates precise PWM signals, enabling smooth driving of motors to each angular position, controlling the slider at ease. To prevent the fruit from getting damaged during the gripping process, force-sensitive resistors (FSRs) are placed in each finger on the TPU balloon where it contacts the fruit, which is shown in (see Fig. 9). These analog sensors provide real-time feedback on the contact pressure between the fingers and the fruit.

The control interface is implemented using Wi-Fi communication, with the ESP32 connected to the local network. Communication occurs bidirectionally with Firebase's real-time database. A custom dashboard is built using HTML, CSS, and JavaScript, which displays the sensor readings and plots graphs and tables to analyze the data. The dashboard provides real-time force data and slider position, providing feedback to the user during operation.

The firmware is written using C++ in Arduino IDE, which includes initializing and calibration of the FSR sensors, real-time PWM control of MG966 servo motors, Wi-Fi connection management, Firebase integration for data transmission using Firebase SDKs, safety logic to prevent over-gripping, and a response handler for the dashboard commands. These integrated combinations allow low-latency wireless communication, feedback monitoring, and intuitive remote interactions, ensuring that the

system is both adaptive and user-friendly.

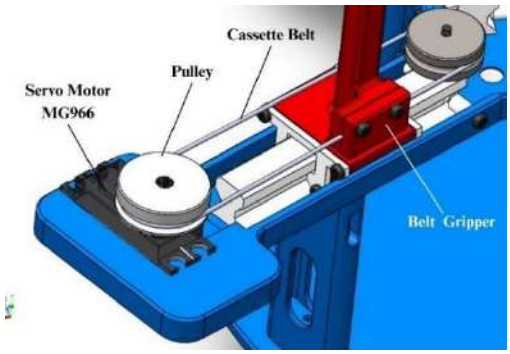

Fig. 5.Pulley Mechanism for the slider

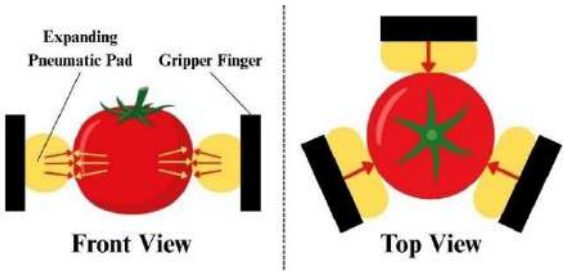

Fig. 6.The way the proposed design will grip the tomato with resulting forces.

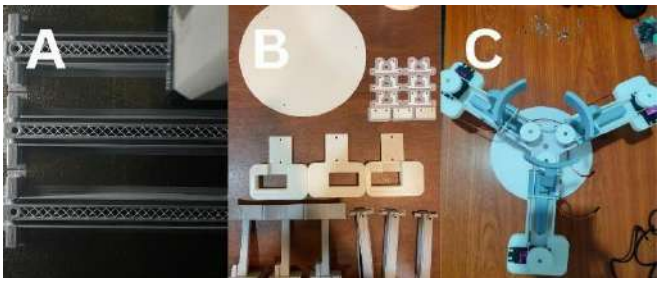

Fig. 7.The fabrication process of the gripper by 3D printing and assembly

4.4 Fabrication process

The fabrication process of the proposed gripper design is described in this section. After finalizing the SolidWorks design, the parts are 3D printed using PLA+ as the material. Then, after the parts are assembled as shown in (see Fig. 8). The three fingers are to distribute the force evenly to the fruit so that the tomato will not be

bruised or damaged, as shown in (see Fig. 6).

The pneumatic system was fabricated using surgical tubes for the pneumatic valves and a mini compressor, which was used to inflate the soft pneumatic balloons shown in (see Fig. 9).

5. THEORETICAL EVALUATIONS

To predict the behavior of the belt-driven adaptive gripper system. This section presents both kinematic and dynamic models, based on the system's parameters and assumptions. By using these models, gripper displacement and forces under ideal conditions can be predicted, and this also serves as a baseline for later comparison with experimental results using regression analysis.

5.1 Kinematic model

The kinematic model describes how rotational motion from the servo-driven pulley is converted into linear displacement of the gripper slider via the belt mechanism. This transformation assumes ideal mechanical conditions without slippage or elasticity.

Table 2 Size ranges of tomatoes

Category	Diameter (mm)	Average mass/ (g)	No of samples
A	35~40	34	5
B	40~45	39.2	5
C	45~50	45.6	5
D	50~55	59.3	5
E	55~60	77.4	5

5.1.1 Pulley rotation to belt velocity: The linear velocity of the belt, and hence the slider, is directly proportional to the angular velocity of the pulley.

$$v(t) = R \cdot \theta(t)$$

This implies that faster pulley rotation results in proportionally faster linear motion of the gripper.

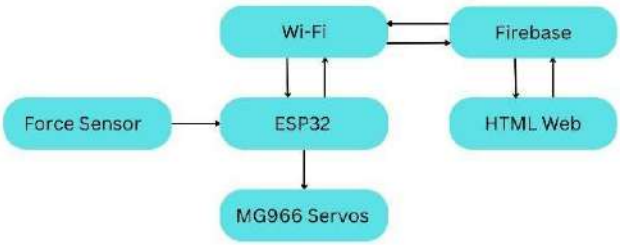

Fig. 8.Electronic layout

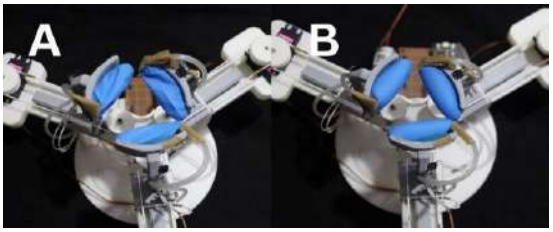

Fig. 9.(A) When the soft pneumatic balloon is not inflated, (B) When the soft pneumatic balloon is inflated.

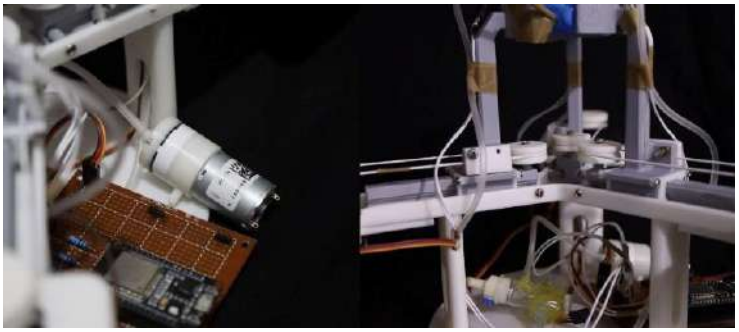

Fig. 10. The fabrication process of the pneumatic balloons with valves and a pump.

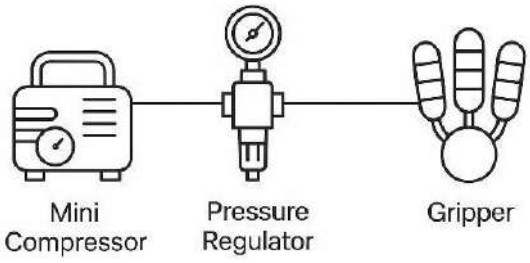

Fig. 11. Pneumatic connection

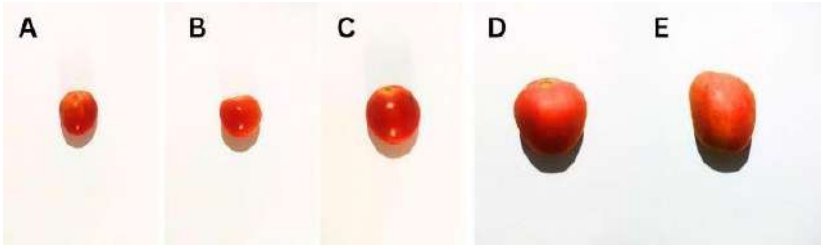

Fig. 12. Categories of tomatoes used for testing (A) 35~40mm, (B) 40~45mm, (C) 45~50mm, (D) 50~55mm, (E) 55~60mm.

5.1.2

Belt motion to linear displacement: The total linear displacement of the slider is obtained by integrating the belt velocity over time.

$$x(t) = \int v(t)\, dt = R \cdot \theta(t)$$

Thus, displacement is a direct function of the pulley's angular displacement, scaled by the pulley radius.

5.1.3

Symmetric gripper travel: In case of two opposing sliders connected to the same belt, their displacements are equal in magnitude but opposite in direction.

$$xL(t) = R \cdot \theta(t)$$

$$xR(t) = -R \cdot \theta(t)$$

This kinematic model forms the foundation for servo-to-position mapping in both simulation and firmware design.

5.2 Dynamic model

The dynamic model evaluates the relationship between applied torque and the resulting linear force and acceleration for the slider, incorporating mass and inertia effects.

5.2.1Newton's law for slider: The net force applied to the slider is equal to the product of its mass and linear acceleration.

$$F = m \cdot \ddot{x}(t) \quad (1)$$

1.2.2Belt Tension and Torque Relationship:

$$T = R \cdot F = R \cdot m \cdot \ddot{x}(t) = R^2 \cdot m \cdot \theta(t) \quad (2)$$

1.2.3Including Pulley Inertia:

$$T = I \cdot \theta((t) + R^2 \cdot m \cdot \theta((t) - (3)$$

1.3Torque to belt tension analysis

Usable stall torque:

$$TUsable = 0.5 \times TStall = 0.5 \times 1.08Nm = 0.54Nm$$

Conversion of torque to tangential force:

$$rpulley = 2/D$$

Torque from the servo is transmitted to the pulley as a tangential force:

$$F_{tangential} = \frac{T_{usable}}{r_{pulley}}$$

Slider force:

$$F_{slider} = m_{slider} \times a$$

Frictional loss:

$$F_{friction} = \mu \times m \times g$$

Belt pretension:

$$F_{pretension} \approx 0.01 \times F_{working}$$

To prevent the backlash and belt slippage, the belt requires a minimum pretension, typically about 1-3% of the expected working tension.

6 EXPERIMENTAL EVALUATIONS

The experimental evaluation aims to assess the functional performance, precision, and adaptability of the developed robotic gripper mechanism in real-world fruit picking scenarios. The key aspects include measuring the accuracy of the slider-driven actuation, the effectiveness of the soft pneumatic fingers in grasping tomatoes of different sizes, and the potential of fruit damage during the picking operation.

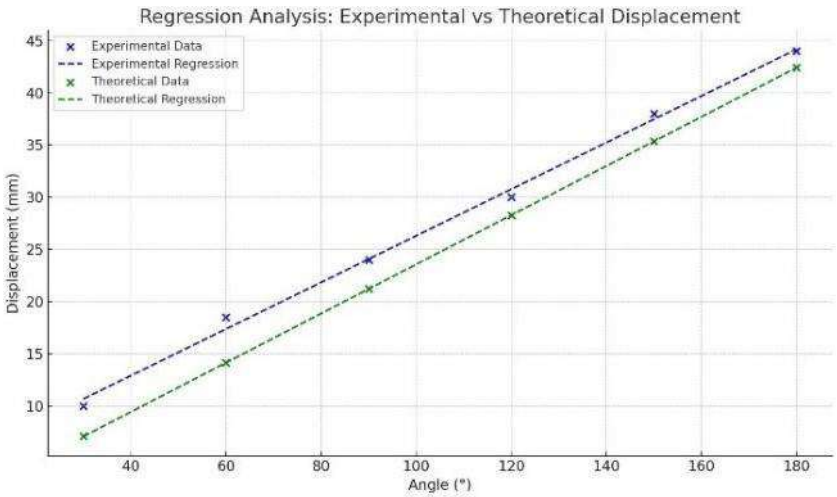

Fig. 13. Regression analysis: Experimental Vs Theoretical Displacement

6.1 Experimental setup

At first, the gripper prototype was placed on a stable flat surface for testing. Each finger was tested individually using an MG966 servo motor connected to a belt-pulley and slider mechanism. An ESP32 microcontroller is used as the central controller, reading data from force-sensitive resistors (FSRs), which are placed at each fingertip where it contacts the fruit when grasping. Pneumatic pads on the fingers are inflated using a mini compressor and a pressure regulator to ensure gentle contact during grasping the fruit, which is shown in (see Fig. 11). Real-time data, including grip force and motor control, is communicated using Wi-Fi to Firebase Realtime Database, and everything can be viewed using the HTML–based dashboard shown in (see Fig. 7).

6.2 Test Procedure

• For slider displacement accuracy, each servo is controlled to specific angles from 0° to 180° and the resulting slider displacement is measured. The theoretical displacement is calculated using $x(t) = R \cdot \theta(t)$ which is recorded for regression analysis.

• For ideal gripping of a tomato at constant pressure without any damage, gripping of tomatoes ranging from 35mm to 60mm were tested to get ideal pressure needed to be given to the balloons for a firm grip of the tomato without damaging it.

• For different sizes of tomatoes, grasping success rates are tested, and each category is grasped three times. A successful grasp is considered as lifting the tomato without slippage or visible deformation.

• For the durability of the gripper, made repetition and durability test is done, performing 30 continuous grip-release cycles to assess mechanical endurance. During the test, position drift, servo responsiveness, and gripper alignment were monitored.

• The gripping force was tested when gripping a tomato with constant pressure (controlled variable), and the force was recorded in a graph using data gathered, as shown in (see Fig 14)

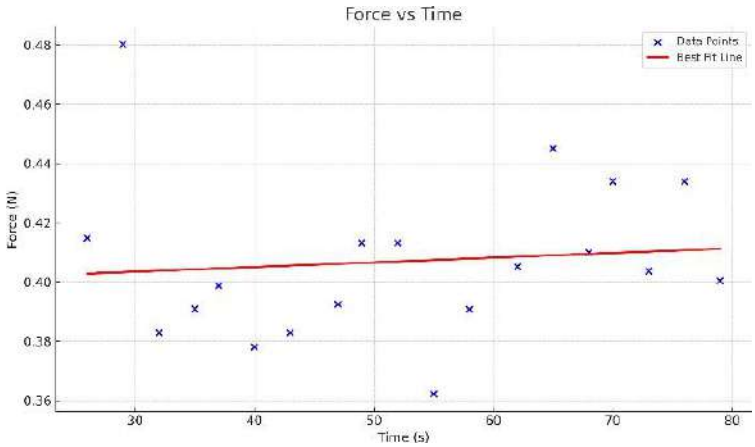

Fig. 14. Force Vs Time for category C tomato at constant pressure of 40kPa.

Table 3 The Theoretical and Measured Displacement to the angle of rotation by the servo

No	Angle (°)	Theoretical Displacement (mm)	Measured Displacement (mm)
1	30	7.07	10
2	60	14.13	18.5
3	90	21.21	24
4	120	28.27	30
5	150	35.35	38
6	180	42.42	44

7. RESULT ANALYSIS

The developed adaptive robotic gripper was experimentally validated for performing displacement accuracy, grasp reliability, and fruit safety. By comparing the theoretical slider displacement derived from kinematic model with measured experimental values across six servo rotational angles, a regression analysis was performed. The results showed that with the increase of the angle the displacement also increases, with slight deviations due to friction and material compliance. The gripping and damage tests were

done at a constant pressure of 40kPa, which was the ideal pressure that could grip the tomato without any damage.

Table 4 Field Testing Results

No	Category	Diameter (mm)	Fruit damage	Successfully gripped or not
1	A	35.5	No	Successful
2	A	39	No	Successful
3	B	41.5	No	Successful
4	C	44	No	Failed
5	D	50	No	Successful
6	D	53.5	No	Successful
7	E	56	No	Successful
	Success		100%	85.7%

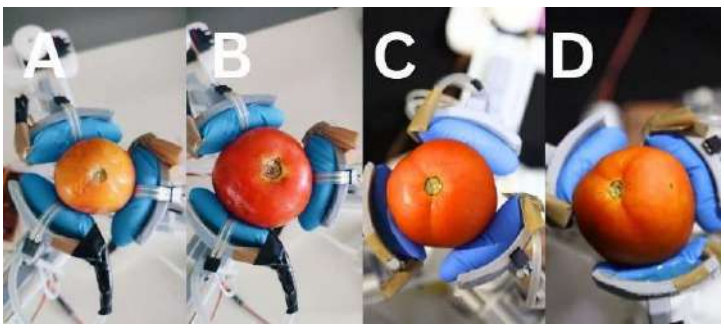

Fig. 15. Grip and damage test done on different sizes of tomatoes A (35-40mm) , B (45-50 mm), C (55-60 mm), D (55-60 mm)

8. CONCLUSION

This research successfully demonstrated the design and development of a bio-inspired adaptive robotic manipulator for fruit picking, focused specifically on tomatoes. By combining a belt-pulley and slider mechanism with soft pneumatic actuators and force-sensitive feedback, the gripper was able to grasp tomatoes of different sizes and shapes without causing any damage. Theoretical kinematic and dynamic models aligned well with the experimental results, which validated the engineering design. The trials performed in the field prove that the gripper is suitable for real-world scenarios with consistent performance, adaptability, and mechanical endurance. The integration of soft robotics, real-time control via ESP32, and a cloud-connected dashboard sets a new benchmark in agricultural automation. Future works will explore full robotic arm

integration, vision-based fruit localization, and autonomous navigation for complete harvesting automation.

ACKNOWLEDGMENT

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Design and Implementation of a Multi Interface Level Measurement System Integration Using Advanced Sensing Mechanism for Palm Oil Separation

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Abstract—This research introduces a capacitive multi-interface level measurement system tailored for palm oil separation tanks, where accurate identification of oil, water, and sludge layers is critical for process efficiency. The sensor features a vertically segmented array of copper plates mounted on an acrylic tube, coupled with a capacitance to digital converter and microcontroller. It captures localized capacitance values influenced by the dielectric properties of surrounding fluids, enabling high-resolution profiling of the tank's contents. Experimental evaluations showed clear permittivity distinctions between palm oil, wastewater, and sludge, facilitating accurate interface localization with sub-centimeter precision. Compared to conventional optical and ultrasonic sensors, the system approaches ±0.5 cm accuracy under opaque, emulsified, and foamy conditions. Additionally, integration with an automated skimmer mechanism demonstrated real time tracking and control of the oil extraction point. This work demonstrates a low-cost, reliable, and scalable solution for automating oil water separation in palm oil processing applications.

Keywords— Multi-interface detection, Palm oil clarification, Real-time process monitoring.

1. INTRODUCTION

Palm oil is a critical agricultural product widely utilized in various industries, ranging from food manufacturing to biofuel production. A pivotal stage in palm oil processing is the clarification phase, where the crude palm oil is separated from residual water and sludge following initial extraction. Typically, the clarification process occurs within large settling tanks where gravity induces the formation of distinct fluid layers. Palm oil rising to the surface, water in the intermediate layer, and sludge settling at the bottom. Efficient separation at this stage directly impacts both oil yield and quality, making precise monitoring and control crucial.

Currently, in many palm oil mills, this separation process predominantly relies on manual observation and operator judgment. Operators visually estimate fluid layer boundaries and manually adjust skimmers or outlet valves accordingly. This subjective method inherently suffers from inconsistency, inaccuracies, and inefficiency. Errors in identifying precise interface levels can result in significant palm oil losses, contamination, reduced product quality, and increased processing costs. Additionally,

manual monitoring exposes operators to occupational hazards associated with high-temperature environments and prolonged observation tasks.

The research here puts forward a new capacitive multi-interface measuring system designed for the use in clarification tanks for palm oil. The developed sensor is a vertical non-conducting tube, inside of which there is a grounded strip of copper attached along the length of half the tube, alongside sixteen tiny plates of copper that are equally spaced, 1 cm apart, on the other half. The entire set of sensing plates, in association with the grounded strip, forms a separate capacitor, the value of whose capacitance significantly varies in accordance with the adjacent medium's dielectric constant, whether air, palm oil, water, or sludge.

The fundamental objectives of the proposed system are to facilitate increased measurement accuracy, improved operating effectiveness, and cost-effectiveness, all irrespective of the reliance on human judgment. Section 2 provides a comprehensive literature review of the existing technologies and the latest developments in multi-interface level measurement systems, including the extraction of palm oil in particular. Section 3 outlines the architecture and approach of the proposed system, including the details of the sensors, electronic integration, and the data acquisition process. Section 4 reports the experimental setup and results, highlighting the performance of the system under varying test conditions. Section 5 makes the results meaningful when juxtaposed with the conventional methods and makes recommendations for improved versions as well as practical implementation.

2. LITERATURE REVIEW

Efficient and accurate interface level measurement is fundamental to optimizing industrial separation processes, particularly in palm oil production. Traditional methods widely practiced in palm oil clarification tanks and decanters involve manual observation and control, often relying on operator judgment to distinguish between oil, water, and sludge layers. While these practices are cost-effective, they are inherently subjective and susceptible to errors, leading to reduced product quality and process inefficiencies [1][2].

To address these shortcomings, researchers have increasingly focused on automated interface detection systems. Among various emerging technologies, capacitive sensors have garnered significant interest due to their simplicity, low cost, and high sensitivity to dielectric changes [3][4]. Traditional capacitive systems typically use a single electrode pair to detect bulk changes in permittivity, which limits their resolution when multiple fluid layers are involved. As a response, segmented capacitive sensors have been developed. These sensors consist of vertically spaced electrodes along a non-conductive medium, allowing localized capacitance measurements and the generation of a one-dimensional electrical capacitance profile (1D-ECP) [5]. This spatial resolution facilitates the detection of sharp and gradual dielectric transitions, which correspond to fluid boundaries, including stable layers and diffuse emulsions [6].

The principle behind these sensors lies in the dependency of capacitance on the dielectric constant (ε_r) of the surrounding fluid. Fluids like air ($\varepsilon_r \approx 1$), palm oil ($\varepsilon_r \approx 2–3$), water ($\varepsilon_r \approx 80$), and sludge ($\varepsilon_r \approx 45–50$) yield distinct capacitance signatures [7][8].

This allows not only the detection of interface locations but also identification of the fluids above and below each interface. Moreover, the real-time data acquisition capability of these sensors enables continuous monitoring and integration into automated systems [9].

Despite these advantages, practical limitations such as temperature sensitivity, sensor fouling, and variation in fluid properties remain significant concerns. Variations in temperature can shift permittivity readings, thereby affecting accuracy. Fouling from oil residues or suspended solids may also alter sensor response over time. To mitigate these issues, researchers have explored hybrid or multi-modality sensing systems that combine capacitive and inductive elements to improve stability and accuracy [10][11]. Such systems offer improved resistance to environmental changes and provide complementary data, enhancing robustness and reliability.

Optical fiber sensors, particularly those utilizing Fiber Bragg Gratings (FBGs), offer another promising method for interface detection. These sensors are lightweight, immune to electromagnetic interference, and capable of multiplexed sensing, making them suitable for harsh industrial conditions [12]. They measure fluid interfaces based on refractive index changes or strain variations, which makes them highly accurate in laboratory conditions. However, in practical palm oil processing, issues like turbidity, opaque emulsions, and suspended solids hinder light transmission, significantly reducing reliability [13].

Ultrasonic sensors, widely used in various industries for level detection, operate by transmitting acoustic waves through a fluid column and analyzing reflected signals to determine layer boundaries. Although effective in cleaning, two-phase systems, their performance deteriorates in palm oil clarification tanks where air bubbles, foam, or emulsions scatter acoustic signals and reduce accuracy [14]. Studies have shown that ultrasonic waves often fail to detect interfaces correctly in the presence of froth or emulsified phases common in palm oil processing [15].

Another approach, Electrical Capacitance Tomography (ECT), has been proposed to create cross-sectional permittivity maps of the fluid column. While ECT systems offer superior spatial resolution, their high cost and complex reconstruction algorithms make them less feasible for large-scale deployment in palm oil mills [16]. Instead, one-dimensional profiling using segmented capacitive arrays provides a balanced trade-off between accuracy and implementation cost [6][17].

Modern control and estimation methods further enhance the applicability of capacitive sensing systems. Integration with microcontrollers and signal processing techniques allows for real-time analysis, thresholding, and compensation for noise or drift. Moreover, model-based control algorithms such as fuzzy logic and Adaptive Neuro-Fuzzy Inference Systems (ANFIS) have shown strong potential in optimizing fluid separation processes. These systems can predict and adjust skimming or valve actions based on trends in capacitance profiles, thus reducing manual intervention and process downtime [18][19]. Compared to optical and ultrasonic methods, capacitive sensors offer a more robust solution in palm oil applications. Optical sensors suffer from light blockage due to turbidity and require clean optical paths, while ultrasonic sensors are

hampered by foamy layers and acoustic scattering. In contrast, capacitive sensors maintain performance even in opaque, emulsified, or multi-phase fluids due to their reliance on electrical properties rather than line- of-sight or acoustic propagation [14][20].

3. METHODOLOGY

3.1 Sensor Construction

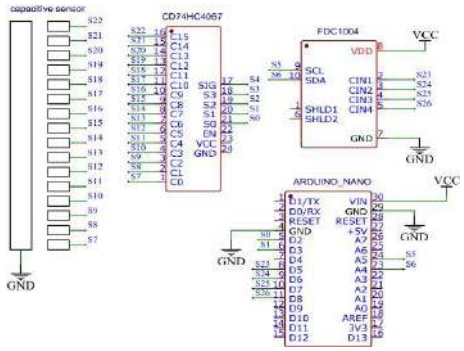

Figure 1: Sensor diagram

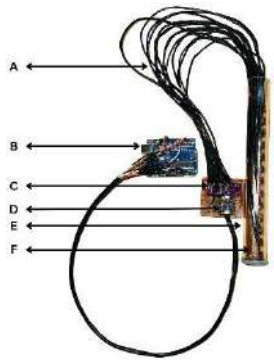

Figure2: Sensor setup

The multi-interface level sensor was constructed using a rigid, vertical acrylic tube as the body and support structure. Acrylic was selected due to its excellent electrical insulation and chemical resistance properties, ensuring isolation of sensing electrodes from direct fluid contact. Sixteen rectangular copper sensing plates, serving as electrodes, were affixed along the length of the tube, each measuring 10 mm in height and 25.4 mm in width. These plates were vertically arranged with a center to center spacing of 40 mm, providing comprehensive coverage across the tank's vertical range. Opposite the sensing plates, a continuous copper strip was installed and grounded, acting as a common reference electrode for capacitive measurements. Each copper plate, along with this opposing grounded strip, formed a parallel-plate capacitor, with the medium (air, palm oil, water, or sludge within the tube) acting as the dielectric material. As fluid levels inside the tank varied, different plates became immersed in different

media, altering the dielectric constant between each plate and the grounded strip, thus changing the capacitance.

Each sensing plate was electrically isolated and connected via shielded leads to the measurement electronics. The spacing between plates defined a vertical resolution of 40 mm, and the 10 mm plate height allowed for a clear overlap with fluid interfaces. The grounded copper strip ensured that electric fields from each plate terminated uniformly, minimizing interference between adjacent sensor plates and confining the sensing volume. Using a non-conductive acrylic tube enabled consistent stratification of fluids (palm oil, water, sludge) inside, analogous to the main tank conditions. The minimal thickness of the acrylic wall ensured negligible impact on capacitance measurements while preventing direct electrical contact with the electrodes. This sensor design provided robust and chemically inert performance suitable for accurately detecting multiple fluid layers.

3.2 Data Acquisition and Electronics

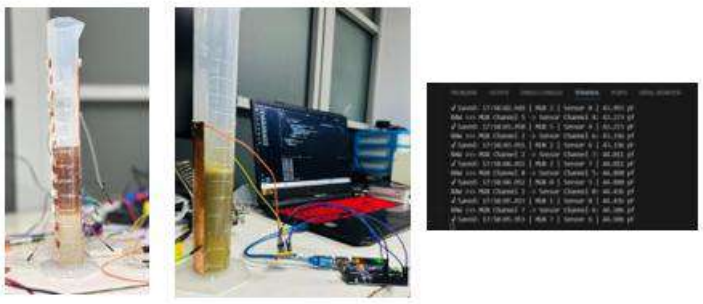

Figure 3: Testing and collecting data

Data acquisition utilized a multiplexed capacitance measurement system to sequentially read each of the 16 sensing plates. A low noise analog multiplexer (MUX) connected each plate individually to a Texas Instruments FDC1004 capacitance to digital converter. FDC1004, featuring four channel high resolution capabilities, converted small capacitance values into digital outputs with femtofarad sensitivity.

The multiplexer cycled through groups of plates, effectively expanding sensor channels. The microcontroller managed the MUX, selecting specific plates and acquiring capacitance data via an I2C interface. The FDC1004 operated in single ended mode with tank ground as a reference, suitable for the grounding provided by the acrylic tube. An internal offset capacitance DAC in the FDC1004 subtracted baseline capacitance, enhancing resolution for small dielectric variations and enabling subtle interface detection.

The microcontroller rapidly scanned all plate capacitances, providing a near real time capacitive profile of the fluid column. Multiple readings per plate were averaged to mitigate noise. This enabled several readings per second, adequate for tracking slow interface dynamics. Data was timestamped and stored with approximately 1 cm spatial resolution through interpolation and subsequently utilized for detailed fluid layer

mapping. The entire electronic system, powered by a stabilized DC source, was shielded to minimize electromagnetic interference, ensuring stable and precise measurements.

3.3 Calibration and Dielectric Analysis

Sensor calibration involved translating raw capacitance data into meaningful interface positions. Initially, baseline air capacitance was measured with the sensor empty, providing reference points for subsequent fluid calibrations. Controlled tests were conducted by fully immersing each plate sequentially in palm oil, water, and sludge to obtain precise capacitance values 42.7 pF (palm oil), 44.7 pF (water), and 45.5 pF (sludge). These differences indicated distinct dielectric properties, with palm oil exhibiting the lowest dielectric constant due to its non-polar nature, and sludge the highest due to conductive particle content. The parallel plate capacitor equation was used:

$$C = \frac{\varepsilon\varepsilon}{0\,d} \quad (1)$$

where $\varepsilon 0$ is vacuum permittivity, ε the dielectric constant, A the plate area, and d the separation distance. This equation facilitated the calculation of effective dielectric constants. Height calibration further refined this model by incrementally filling the tube and logging capacitances, verifying sensor linearity, and defining the relationship between partial immersion and capacitance. This established clear equations and lookup tables for converting capacitances to precise interface positions and fluid layer thicknesses.

3.4 Gradient Detection and Interface Mapping

Following calibration, the sensor provided a detailed vertical capacitance profile, enabling interface detection via numerical gradient analysis.

$$\Delta c = c_{i+1} - c_i \quad (2)$$

The discrete difference between adjacent plates, defined as highlighted interfaces as significant capacitance shifts. Small differences indicated uniform fluid presence, while larger jumps revealed fluid interfaces. Negative ci values corresponded to transitions from higher dielectric media (water) to lower dielectric media (oil), clearly defining interfaces. Partial immersion cases were managed through an interpolative model,

$$C_{partial} = \frac{s_0}{d}\ [\,k_1 A_1 + k_2 A_2\,] \quad (3)$$

To enhance the spatial resolution of interface detection within the segmented capacitive sensor system, the partial capacitance model was employed. This expression models each sensing plate's capacitance as a weighted contribution of two dielectric materials occupying adjacent regions above and below a fluid interface. This layered-area approach accounts for partial coverage of a plate by two distinct media (e.g., oil and water), thereby allowing continuous rather than binary fluid identification. The model is particularly useful when an interface lies between two plates or cuts through a plate's sensing volume. It enables sub- centimetre precision in estimating interface positions by

interpolating capacitance values across dielectric gradients. Additionally, this formulation allows the detection of complex emulsion layers commonly referred to as rag layers whose dielectric properties change gradually with height. Such analytical capability enhances the robustness of the sensor in industrial oil-water separation tanks, where fluid boundaries are often unstable or non-sharp.

3.4 Skimmer Control Mechanism

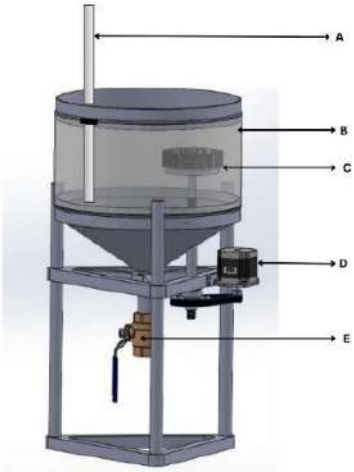

Figure 4: Design of skimmer process (A- Sensor, B – Pilot tank, C- Skimmer, D – Stepper motor, E – Outlet valve)

The sensor system was integrated with an automated skimming mechanism designed to precisely extract palm oil layers without cross contamination. A stepper motor controlled the skimmer's vertical position with fine incremental adjustments. Continuous analysis of the capacitive profile informed the microcontroller of real-time oil-water interface positions. The skimmer was dynamically positioned slightly above this interface within the oil layer, optimizing extraction and preventing water uptake.

The microcontroller continuously analyzes the capacitance profile to determine the real time height of the oil water interface. Once the interface is detected and its height is calculated, the microcontroller commands the stepper motor to lower the skimmer to the appropriate depth. The target position for the skimmer is set a short distance below the oil surface but still above the oil water interface within the oil layer near its bottom to ensure maximum oil extraction while avoiding water ingress.

The control algorithm operates through a feedback loop. As the skimmer draws off oil, the oil layer thickness decreases, and the interface begins to move downward. The capacitive sensor array instantly detects this change as plates that were in oil start sensing water. The microcontroller responds by incrementally lowering the skimmer to follow the descending interface. This dynamic tracking continues until the oil layer reaches a predefined minimum threshold or another process limit is encountered, ensuring efficient and controlled separation.

4. RESULTS

The experimental calibration results confirmed distinct capacitance height characteristics for each fluid tested. Using a parallel plate copper capacitor (plate height 161 mm, width 20 mm, gap 40 mm) partially immersed in a fluid, capacitance increased linearly with immersion height in all cases. Figure 4 shows the measured capacitance vs. immersion height for palm oil, water, and sludge. The slopes of these curves differed markedly, reflecting the fluids' different dielectric constants. From the slope and the known geometry (plate area and separation), the relative permittivity of each fluid was calculated based on the parallel plate capacitance formula,

$$C = \varepsilon \frac{A}{d} \tag{4}$$

The extracted values for palm oil, water, and sludge were consistent with expectations: The palm oil sample's permittivity (~2.2) closely matched reported values for crude palm oil (~2.1), and the water sample's (~78) was near the standard value of 80 at room temperature. The sludge sample showed an effective permittivity of approximately 45–50, significantly higher than pure oil, which is reasonable given that sludge is essentially a water rich phase indeed, prior studies show that adding water to palm oil can raise its effective from ~3 up to ~63 as water content increases. These calibration results verified that the capacitance-vs-height method can accurately determine fluid dielectric constants, confirming the sensor's ability to distinguish the three phases by permittivity.

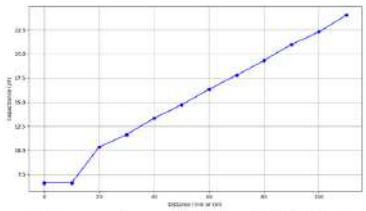

Figure 5: Measured capacitance vs height level of oil

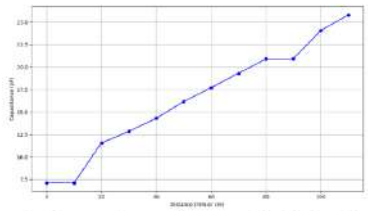

Figure 6: Measured capacitance vs height level of sludge

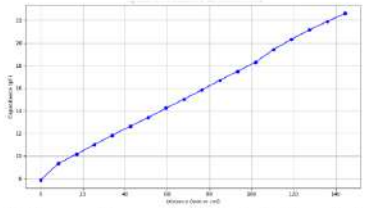

Figure 7: Measured capacitance vs height level of water

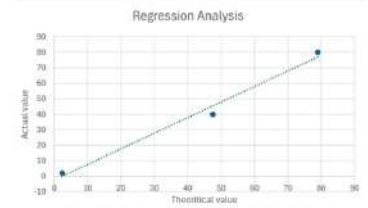

Figure 8: Actual value vs Theoretical value

Table I: Measured permittivity and literature permittivity.

Fluid	Measured permittivity	Literature permittivity
Palm oil	~2.35	2.1 (crude CPO) [7],[8]
Water	~79	80.1 (pure water, 20 °C)
Sludge (palm oil effluent)	~45	20–60 (emulsion/sludge)

After establishing the permittivity's, a segmented capacitive level sensor was constructed and tested for

multi-layer interface measurement. The sensor consisted of a vertical acrylic tube (acting as an insulating support and container) equipped with 16 copper sensing plates (electrodes) arrayed along its height, plus a continuous copper strip on the opposite side serving as the ground reference. Each sensing plate was 10 mm in height and 25.4 mm in width, with a 10 mm vertical gap between adjacent plates, resulting in a segmented array that covered a total active height of 16 cm. Essentially, each small plate formed a localized parallel- plate capacitor with the grounded strip across the tube wall. The sensor interface electronics were designed to sequentially read each segment's capacitance at high resolution. A multiplexing unit (MUX) addressed each plate in turn, and an FDC1004 capacitance-to-digital converter (from Texas Instruments) digitized the capacitance with femtofarad sensitivity. The system sampled all 16 channels to produce a discrete capacitance profile with a spatial resolution of 1 cm (the plate spacing). To minimize noise and interference, all signal cables were shielded. The connection wires were wrapped in aluminum foil linked to circuit ground (and tied into the FDC1004's driven shield output), effectively creating a Faraday shield around the sensor leads. This shielding method substantially reduced spurious capacitance fluctuations by shunting environmental electric fields to ground. As a result, the sensor readings for each segment were stable and repeatable, with negligible noise after filtering, providing a clear stepwise capacitance profile along the height of the column.

The segmented sensor successfully measured multiple fluid layers and their interfaces in a stratified three- phase test.

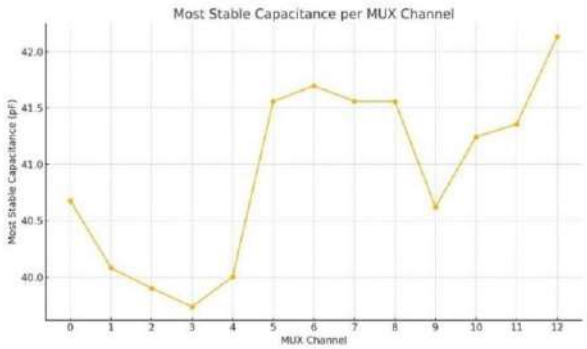

Figure 9: Capacitance profile.

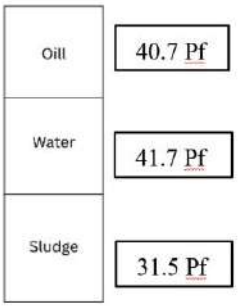

Figure 10: Capacitive profile

Fig 9 presents the capacitance profile obtained when the sensor was inserted into a column containing three layers palm oil on top, water in the middle, and sludge at the bottom. Each data point in the profile corresponds to the capacitance measured by one 10 mm segment, plotted as a height function from the oil surface. The results demonstrate distinct plateaus and sharp transitions in the capacitance versus height curve that directly correlate with the fluid layers. In the top region, where the sensor plates were surrounded by palm oil, the measured capacitance remained low, consistent with oil's relative permittivity. Moving down to around the 5 cm mark, a sudden jump in capacitance is observed in the profile, indicating the oil water interface. Below this interface, the capacitance readings at each successive plate are much higher than the plateau corresponding to the water layer, given water's high permittivity. A second transition is evident near 13 cm depth, where the capacitance values change again as the sensor enters the bottom sludge layer. Notably, the capacitance in the sludge layer is slightly lower than in the pure water region. These two transition points in the profile align closely with the visually observed layer boundaries in the column, confirming that the sensor can pinpoint the vertical positions of both the oil water and water sludge interfaces. The multi-layer test also highlights the layer identification capability. The top segment readings matched the calibrated value for oil, the middle segments matched water's permittivity, and the lower segments indicated a different high permittivity medium (sludge). Thus, by comparing each segment's capacitance to the known calibration values (from the single fluid tests), the system effectively identified which fluid occupied each segment of the column.

Throughout these experiments, the segmented capacitance sensor exhibited high spatial resolution and accuracy in detecting interfaces. The 1 cm segmentation inherently defines the measurement granularity. However, the interface could often be located at a finer precision than one segment length by analyzing the gradient between adjacent segment readings. Overall, interface positions could be determined to within roughly ±0.5 cm. In addition, the real time permittivity profile captured any diffuse interface regions. If an emulsion layer or gradual transition were present, it would manifest as a more distributed change in the capacitance profile rather than a sharp step. Finally, it was observed that implementing the cable shielding and proper grounding was crucial for achieving these precise results. Without shielding, environmental noise caused fluctuations of several femtofarads in the raw readings. After wrapping the sensor cables

in grounded aluminum foil and using the FDC1004's active shield drive, the noise floor improved dramatically, yielding clean capacitance vs. height curves.

5. DISCUSSION

5.1 Sensor Accuracy and Interface Detection

Experimental validation of the segmented capacitive sensor system verifies its capability of providing high-resolution, real-time identification of the different interfaces during palm oil refining process. The huge difference in the dielectric constants of palm oil ($\varepsilon_r \approx 2.2$), water ($\varepsilon_r \approx 80$), and sludge ($\varepsilon_r \approx 45–50$) made accurate identification of the fluid layers within reach. These differences, determined through vertical profiling of capacitance, allowed the system to distinguish fluid interfaces with a certainty of about ±0.5 cm, significantly better than the conventional manual estimation methods used in most palm oil clearance ponds [1][2].

5.2 Robustness in Harsh Industrial Conditions

One of the inherent benefits of the system is the robustness in harsh environments. Unlike optical sensors, that require an open line-of-sight and are thus often halted by turbidity, emulsions, or solid particulates [5], the capacitive sensor is able to sense the change in permittivity, thus being insensitive to optical obscurity. Similarly, ultrasonic sensors are less effective due to foam or air bubbles in suspension, that hinder the transmission of signals [7]. In contrast, the capacitive sensor performs optimally regardless of the opacity of the fluid or the presence of bubbles, as its measurement is purely dependent on the dielectric properties [3].

5.3 Permittivity Profiling and Anomaly Detection

Furthermore, the sensor has capabilities that go beyond simple binary detection, including the ability to provide a continuous permittivity profile down the vertical axis. The characteristic enables the detection of unstable or ill-defined emulsion layers that are normally found in the interfacial region between oil and water in industrial storage containers. Furthermore, the system's ability to classify the material according to localized capacitance enables the identification of abnormalities, such as unintended layering or sludge build- up, enhancing safety and quality assurance procedures during the production line.

5.4 Integration with Automated Skimming

From a regulatory perspective, the integration of this sensor with a automated skimming device enables the precise elimination of the oil layer and the exclusion of water and sludge. These innovations maximize the production of products and reduce contamination, thus curtailing the necessity for reprocessing and energy use. In automated applications, the real-time feedback provided by the sensor is useful for the control of dynamic skimming and allows immediate action for the response of aberrant interface changes [4][8].

5.5 Comparison with Existing Technologies

Compared to other multi-sensor arrangements, such as hybrid capacitive-inductive sensors [4] and Electrical Capacitance Tomography (ECT) sensors [8], the proposed segmented sensor is distinguished by its simple structure, relatively low cost, improved ease of calibration, and high sensitivity. Although ECT sensors hold high potential, because of their sophisticated reconstruction methods and high costs of the devices, they are less suitable for implementation in standard palm oil mills [8].

5.6 Limitations and Future Enhancements

Despite the benefits, the system is faced with some limitations. Temperature differences could affect the dielectric constants, thus the capacitance readings. These differences are compensated for using temperature compensation methods or hardware calibration [10]. In addition, the deposit buildups on electrodes for prolonged use could also interfere with accuracy, thus the need for frequent maintenance or the use of automated cleaning systems. Nevertheless, the simplicity, reliability, and affordability of the designed scheme make this approach highly viable for wide-scale industrial production.

5.7 Industrial Relevance and Scalability

Briefly, the segmented capacitive sensing system offers an outstanding and cost-effective method for the automated assessment of interfaces in palm oil split operations. Its effective performance in demanding and turbid environments, in addition to its real-time profiling and integration capabilities, represents a significant step forward relative to available technologies. The results recorded in the experimental studies performed in the past by [2], [3], [4] validate that the approach meets commercial-grade specifications for strong, accurate, and low-maintenance process measurement.

5. Discussion

The developed capacitive segmented sensor system offers an effective and technologically advanced means of interfacial detection in palm oil processing. The differentiation of the oil, water, and sludge from relative permittivity enables accurate real-time profiling of the fluid. The high resistance of the sensor to opaque and emulsified conditions, coupled with high spatial resolution and low maintenance requirement, significantly eliminates major limitations of conventional methods. The use of a stepper motor-operated skimmer has demonstrated effective real-time control, thus optimized the extraction of the oil and minimized the risk of cross-contamination. Although temperature drift and prolonged fouling are areas that need correction, the system demonstrates high prospects for commercial use. In general, the system significantly enhances the automation of the separation process in palm oil mills, thus enhancing efficiency, consistency, and sustainability.

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Smart Waste Sorting Robot: Vision Guided System for Sustainable Urban Waste Management

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Abstract—Waste separation at collection points remains a major challenge in sustainable waste management, especially in developing countries. Traditional manual sorting is time-consuming, inconsistent, and unable to handle the growing volume and complexity of mixed waste. This paper presents the design and development of a smart waste sorting robotic system for use at waste collection points where large quantities of mixed waste are dumped. The proposed system categorizes six types of waste materials – Plastic, Glass, Aluminum, Paper/Cardboard, E-waste, and Polythene – using a vision-guided Convolutional Neural Network (CNN) on a Raspberry Pi 3 Model B+ with a Logitech C270 camera. The camera captures images of waste items, which are processed in real-time using a TensorFlow-trained CNN (deployed with TensorFlow Lite) for classification. Classified results are simultaneously logged to a Firebase cloud database for monitoring. A 6-DoF robotic arm (built with MG996R and SG90 servo motors) then places each object into one of six bins arranged at specific angular positions around the arm. The compact system can be installed in local waste centers and is robust enough to handle varied waste streams. With AI-based image processing, real-time IoT integration, and automated mechanical sorting, the system operates with minimal human intervention. A Flask-based web dashboard provides real-time visualization of classification results and bin status. Initial trials indicate high classification accuracy and reliable robotic motion. This study addresses a critical gap in automating waste segregation at the source, potentially reducing labor requirements, contamination of recyclables, and inefficiencies in downstream recycling operations.

Keywords—Convolutional Neural Network (CNN Waste Classification), Image Processing, Internet of Things, Smart Waste Management, TensorFlow

1. INTRODUCTION

The urbanization and industrialization of the last decades resulted in a tremendous increase in the production of municipal solid waste all over the world. Traditional waste management facilities, particularly in developing countries, continue to rely heavily on manual segregation methods, which are often inefficient, labor-consuming, and dangerous. With increased complexity and quantity of waste, flaws in the traditional manual segregation process came to light, prompting scientists to increasingly rely on automation and intelligent technology more effectively for more effective waste separation.

The integration of computer vision, robotics, and artificial intelligence (AI) has been a successful answer for the enhancement of waste sorting methods. Deep learning, using Convolutional Neural Networks (CNNs) has made it possible to train a machine to

acquire visual patterns and sort objects correctly. Several studies over the past couple of years have investigated the effectiveness of AI-controlled automated waste sorting [1]. For instance, a robot system is developed on the basis of object detection where YOLOv6 was combined with a 4-DOF robot arm and achieved efficient real-time waste sorting and identification using a geometric inverse kinematics approach. The study demonstrated how robust object localization combined with motion planning for robots can be utilized to augment autonomous waste manipulation. Similarly, another robot system developed a smart bin that incorporated YOLOv4 on Raspberry Pi so that the system was able to recognize classes of waste and direct movement of the bin lid appropriately. While effective for real-time operation, it was routine for implementing advanced object detection models in such systems to demand additional computational power or be limited to specific classes of waste.

Other researchers have sought specialized object detection models for embedded systems. Ma et al. and Melinte et al. used the application of light variants of Single Shot Detector (SSD) for faster inference and reduced computational load. These solutions established the feasibility of running AI models on low hardware platforms such as Raspberry Pi, but often required sensitive trade-offs between speed and accuracy, especially under noisy or real-world conditions [2].

In addition to image-based classification, sensor-based approaches have also been explored. Fitzwalter Ang et al. built an intelligent mobile robotic system that employed capacitive and metal sensors to differentiate waste to sort material that is being conveyed on a conveyor belt to the appropriate bins. While the system worked well in laboratory environments, it was not flexible to visually distinct or overlapping types of waste that are common in actual waste collection scenarios. [3]

Overall, these studies point towards a growing trend of using AI and robots to enhance waste management system efficiency. Detection algorithms such as YOLO and SSD have been extremely efficient in detecting multiple items of garbage simultaneously and traversing sorting systems in real-time. However, such models typically get training on bounding box annotations and may not perform as well when only one object is being displayed at a time or when the system should be easy to implement and lightweight. One alternate path, widely taken in several waste classification systems, is single-label image classification using CNNs. The strategy here is to train the model for the classification of the broad category of an image, which is best applied in settings where waste items are segregated in a frame of control. CNN-based classifiers have the advantage of being computationally less intensive than entire object detection models, but with the challenge of carrying good performance in recognizing texture, shape, and material features of waste items. Recently, classification powered by AI has also been integrated with robotic arms to physically sort the waste into proper bins. Joint control and object gripping are most often utilized by servo motors and grippers, respectively, and human-like sorting is mimicked. Together, vision-based classification and mechanical actuation, new intelligent sorting technologies pursue greater precision, minimal human intervention, and even continuous performance across different waste flows. [4]

As sustainability of the environment becomes more of an issue, the development of effective, cost-conscious, and intelligent waste sorting technologies remains a steady go-to in research emphasis. With the implementation of machine learning and embedded system technologies, the technologies can revolutionarily change the traditional means of managing waste, particularly in urban and developing worlds where manual sorting is still common.

2. METHODOLOGY

The proposed waste sorting solution is an AI-driven robotic system that integrates hardware, software, and control components into a layered architecture for real-time image acquisition, machine learning-based classification, robotic arm manipulation, and bin segregation. Fig. 1 provides a CAD model of the robotic arm and bin arrangement used in the system. The overall workflow (illustrated in Fig. 3) begins with capturing an image of the waste item, then processing it through the CNN classifier. The identified material category is mapped to a specific bin location, after which the robotic arm moves to deposit the item in the correct bin. This section details the system's three main layers and their interactions.

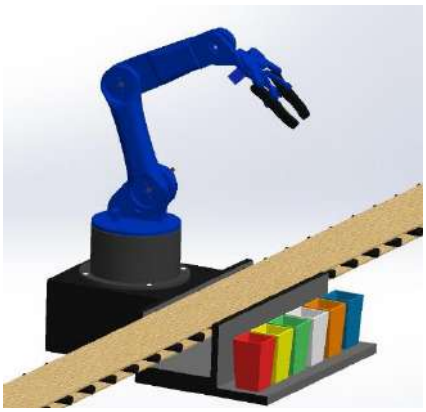

Fig. 1. SolidWorks CAD model of the 6-DoF robotic arm and its base

2.1. Hardware Layer

The hardware layer of the proposed system consists of several integrated components that enable real-time data acquisition, robotic actuation, and overall system control. At its core is the Raspberry Pi 3 Model B+, which acts as the primary processing unit responsible for coordinating the classification and sorting tasks. A Logitech C270 HD webcam, fixed in position, captures images of individual waste items as they are presented for classification. This camera provides sufficient resolution (720p) to support the visual recognition process. A custom-built six-degree-of-freedom robotic arm forms the actuation mechanism, employing MG996R servo motors for high-torque joints and SG90 micro servos for finer movements and gripper control. These motors enable precise rotation, lifting, and gripping actions necessary for waste collection and

disposal. The structural frame and supporting bin arrangement are designed to allow the robotic arm to reach and sort waste into one of six bins positioned around it in a semi-circular layout. [5]

2.2. Software Layer

The software layer integrates machine learning, image processing, real-time inference, and web-based interaction. A TensorFlow-trained Convolutional Neural Network (CNN) model, optimized with TensorFlow Lite for deployment on Raspberry Pi, forms the core of the waste classification process.

The model was trained on a dataset of over 15,000 images across six categories: plastic, glass, aluminum, paper/cardboard, polythene, and e-waste. Images captured by the webcam are preprocessed using OpenCV, normalized, resized, and fed into the CNN model for classification. Based on the model's prediction, the system identifies the corresponding waste category with a confidence score. The results are then transmitted to a Firebase cloud database for logging and remote monitoring. Additionally, a Flask-based web interface hosted on the Raspberry Pi provides a real-time dashboard displaying the live camera feed, predicted labels, and category-wise sorting statistics. This interactive visualization helps users and facility operators to monitor system performance without direct physical access to the hardware. [6]

Fig. 2. Waste images used for training model

Fig. 2 shows sample images from each waste category in the dataset. The images were collected from public waste image repositories and augmented where necessary to increase diversity (variations in lighting, background, object size, etc.). CNN was trained for 30 epochs, achieving high training accuracy. (over 90%)

2.3. Control Layer

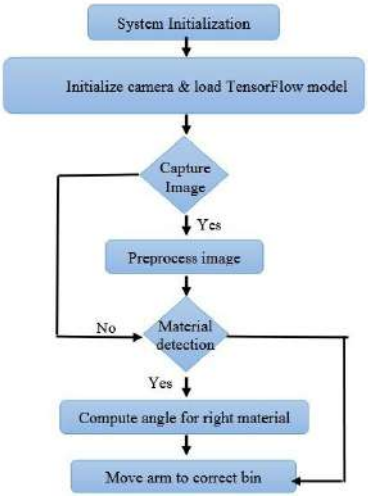

Fig. 3. System workflow flowchart

The control layer serves as the bridge between the classification output and the mechanical execution of sorting tasks. Upon receiving the predicted waste category, the system computes the angular position of the appropriate disposal bin relative to the robotic arm's base. These bins are arranged at specific angles, ranging from −45° to +45°, at 15° intervals to facilitate rapid and accurate positioning. The control software translates this bin angle into corresponding pulse-width modulation (PWM) signals sent through the Raspberry Pi's GPIO pins to the servomotors. The base servo rotates the arm toward the correct bin, while other servos adjust the arm's posture to reach the target position. The gripper, controlled by an SG90 micro servo, securely grips the object and releases it above the bin once aligned. A simple trajectory control mechanism ensures smooth acceleration and deceleration of the arm, minimizing mechanical strain. The system then returns the arm to its home position, ready for the next classification and sorting cycle. [7]

Figure 3 illustrates the overall control flow of the system. Starting from system initialization (camera setup and model loading), each cycle involves capturing an image, preprocessing, classification, then if a material is detected (identified class), computing the target angle and moving the arm to drop the item in the appropriate bin. The process repeats for each new item, enabling continuous operation.

3. RESULTS AND DISCUSSION

This section evaluates the performance of the AI-powered robotic waste sorting system. The primary metrics of interest are the CNN model's classification accuracy on both training and validation data, and the overall effectiveness of the integrated system in real-world sorting tasks. CNN was trained in over 30 epochs.

Fig. 4. Training and Validation accuracy over 30 epochs

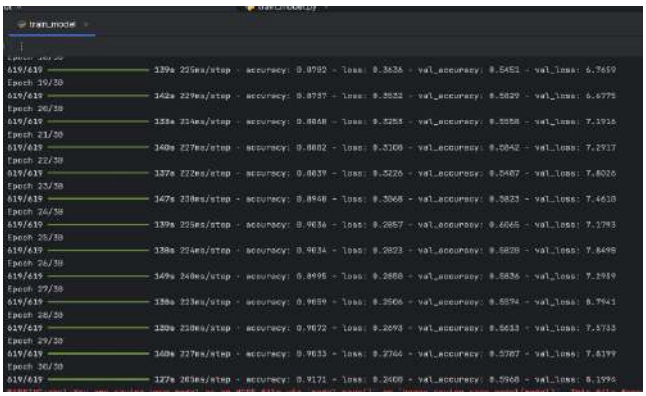

Table 1 summarizes the final training results achieved, and Fig. 4 presents the model's accuracy trend during training.

TABLE **1**. Training model accuracy

Data	Result
Final training accuracy	~91.7%
Final validation accuracy	~59.6%
Final training loss	~0.2400
Final validation loss	~8.1994

The results indicate that the model learned the training data very well, achieving over 91% accuracy on the training set. However, the validation accuracy peaked at around 60%, which reveals a significant generalization gap. In fact, the highest validation accuracy observed was ~60.65% at epoch 24, after which it slightly declined or plateaued. This gap between training and validation performance suggests the model is likely to be overfitted with the training dataset. Despite using a substantial number of training images (15k+), the diversity of the data may not have been sufficient to cover all variations the model encounters in validation or real-world scenarios. The relatively high validation loss (~8.2) compared to training loss (~0.24) further underscores the model's struggle to generalize.

Despite the moderate performance on the held-out validation data, initial real-world trials of the integrated system were encouraging. In a controlled lab setting with

properly positioned items and consistent lighting, the system was able to correctly identify and sort most presented waste items in real time. The high training accuracy translated to confident predictions on those items that resembled the training examples. We observed that plastics, metals (aluminum cans), and glass bottles were usually identified correctly. Paper vs. polythene was a more common confusion (as expected, given their visual similarity in some cases), and the model sometimes struggled with e-waste unless the electronic item had distinctive features. Overall, the mechanical sorting via the robotic arm proved reliable: the servos moved accurately to each bin and deposited items without spillage. The entire cycle time (image capture to sort complete) averaged about 3–4 seconds per item, much of which was the arm movement rather than the computation. [8]

Another positive outcome was the seamless integration of the IoT and dashboard features. The Firebase logging worked in real time, creating a record of each sorted item which can be later analyzed (for example, counting how many plastics were sorted in a day). The Flask web dashboard (Figure 5) provided instant visual feedback. As an example, when an aluminum can was placed and identified, the dashboard displayed the label "Aluminum" with a high confidence score, updated the count for Aluminum category, and highlighted the corresponding bin status. Similarly, for a piece of paper, the interface would show "Paper" and increment that count. This real-time monitoring is valuable for verifying system operation and could be extended with features like alerting when a bin is full or when an unidentifiable item is rejected. [9]

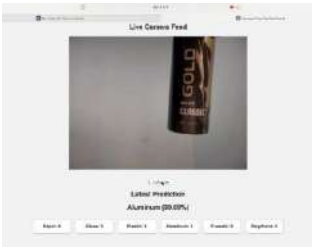

Fig. 5(a) Detection of paper waste *web dashboard*

Fig. 5(b). Detection of Aluminum waste *on web on dashboard*

It is important to address the gap in model accuracy for broader deployment. The current results emphasize the need for further training data enhancements and possibly more robust models or techniques (discussed in the next section). However, even at ~60% validation accuracy, the system's practical performance in a controlled environment was higher because many misclassifications in validation occurred on edge-case images. In a real scenario, if the system is unsure about an item (low confidence), it could be programmed to discard or send the item to a "miscellaneous" bin rather than risk contamination – an aspect for future improvement. [10]

In summary, the proposed vision-guided sorting robot successfully demonstrates the feasibility of automating waste segregation at collection points. It combines off-the-shelf hardware and open-source software to create a low-cost solution. The results show that while the concept is sound, there is room for improving the AI model's generalization. Nonetheless, the mechanical sorting aspect is effective, and the integrated system can

reliably handle single-item sorting. This lays a strong foundation for more advanced versions of smart waste sorters.

Future enhancements to the proposed system aim to improve its accuracy, robustness, and adaptability in real-world scenarios. One key direction is optimizing the classification model by exploring lightweight deep learning architectures such as MobileNetV2 or Efficient Net-Lite, which are better suited for embedded platforms like the Raspberry Pi. Transitioning from single-label image classification detect objects using models like YOLOv5 or YOLOv8 could enable the system to detect and sort multiple waste items within a single frame, especially in cluttered environments. Expanding and diversifying the dataset with images captured under various lighting conditions, backgrounds, and object states will help improve generalization and reduce overfitting. Additionally, incorporating transfer learning from pretrained networks may boost classification accuracy while reducing training time. Another valuable improvement is integrating anomaly detection to identify hazardous or unclassifiable waste and route them to a designated bin. Finally, the system could be connected to a broader smart waste management infrastructure by interfacing with smart bins, automated alerts, and IoT dashboards, allowing for scalable deployment across communities and municipalities. [11]

4. CONCLUSION

This project demonstrated the development of an AI-driven robotic system for smart waste classification and sorting using machine learning and embedded robotics. A CNN model trained on over **15,000 images** across six waste categories (Plastic, Glass, Aluminum, Paper/Cardboard, Polythene, and E-waste) was able to achieve high training accuracy (~91%) and a peak validation accuracy of about 60%. Using a Raspberry Pi 3 B+ as the controller along with a Logitech C270 camera, the system performs real-time image classification of waste items. The classification output drives a 6-DoF robotic arm (with MG996R and SG90 servos) to physically sort each item into one of six bins arranged in a 180° semicircle (with 30° interval positions, e.g., bins at -45°, -30°, -15°, +15°, +30°, +45°). This integration of deep learning, IoT, and robotics enabled automated waste sorting with minimal human intervention.

In experimental trials, the system operated reliably in a controlled environment: it accurately identified and sorted most waste items placed in front of it, validating the end-to-end functionality. The addition of more images for certain classes (like paper) during training was found to improve the model's recognition ability, illustrating the importance of dataset quality on performance. The entire setup is relatively low-cost and compact, making it suitable for deployment in local collection centers or small recycling facilities. By automating initial segregation of waste at the point of origin, the system will be able to minimize manual labor, decrease the risk of cross-contamination of recyclables, and enhance the efficiency in the recycling loop. [12]

Despite its successes, the system has limitations, such as the moderate performance of the model on unseen data and the one-object-at-a-time assumption in sight. The results highlight that there is still more optimization to be achieved before the system can be deployed in yet more uncontrolled real-world environments. Nevertheless, this piece of work illustrates a viable approach to smart waste collection, combining AI-driven vision

and robotic actuation to address an urgent environmental issue. It is a precursor to more sophisticated waste sorting technologies that could have a transformative effect on city and community management of solid waste. [13]

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Brain-Controlled EEG Interface For Real-Time Robotic Actuation In Assistive and Rehabilitation

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Abstract—This research demonstrates the successful creation of a low-cost, real-time electroencephalography (EEG)-based brain-computer interface (BCI) system designed for accurate neuro-robotic actuation, on/off switching of robotic actuators, with the aim to promote assistive and rehabilitation technologies in resource-constrained environments. The project addresses significant limitations of prevailing EEG-based BCIs, such as bulky electrode setups, high costs, long setup durations, low user adaptability, and a lack of real-time processing, all of which limit their everyday use. We developed a simplified 6-channel dry electrode array (C3, C4, Cz, FC3, FC4, Fz) based on the 10-20 system for picking up motor imagery signals (mu: 8–12 Hz, beta: 13–30 Hz) to produce on/off controls for actuators. The system is implemented using low-cost hardware, such as AD620 instrumentation amplifiers (gain: ~100), TLC277CP op-amps for filtering (0.5 Hz high-pass, 49.4 Hz low-pass), and an Arduino Uno for analog-to-digital conversion (10-bit, 40 Hz/channel). Advanced signal processing comprises Common Spatial Pattern, wavelet transforms, and Independent Component Analysis for aggressive noise removal, augmented by hybrid CNN-LSTM models for quick and accurate classification of user intent. Rigorous validation with the BCI Competition IV 2a dataset and real trials in multiple applications—prosthetic control, wheelchair control, and rehabilitation robotics—produced classification accuracies of 82–92%, signal-to-noise ratios of 13–16 dB, response times under 200 ms, and information transfer rates of 1.3–1.8 bits/s. With a setup time under 5 minutes, and incorporating features like cloud-based data storage for real-time signal logging and dual hardware/software filters for best-in-class signal clarity, this BCI system promises scalability, usability, and affordability. By the inclusion of low-cost components, minimizing training time, and maximizing flexibility for a range of applications, this research significantly pushes the availability of neuro-robotic solutions for assistive devices, home healthcare systems, and rehabilitation equipment. It empowers individuals with motor disabilities in low-income regions, fostering inclusive advances in neuro-engineering and enhancing quality of life with beneficial, innovative technology.

Key words - Brain-Computer Interface, EEG, Neuro-Robotics, Dry Electrodes, Motor Imagery, Signal Processing

1. INTRODUCTION

EEG-based BCIs are revolutionizing human interaction with robotic systems using mere control by brain signals without movement [1], [2]. These technologies are at the heart of enabling people with disabling mobility or neurological disorders through new opportunities in assistive devices and rehabilitation [3], [4]. By detecting brain patterns, such as motor imagery signals in the mu (8–12 Hz) and beta (13–30 Hz) bands, BCIs can convert a subject's thought into robot actuator commands so that activities such as operating prosthetics or operating wheelchairs are facilitated [5], [6]. Yet, restrictions in the form of complex electrode installations, expensive devices, lengthy preparations, and slow real-time processing confine the applicability of such systems, especially for users in resource-constrained areas [7], [8]. This work presents a low-cost, real-time EEG-based BCI system for on/off control of robotic actuators with a focus on maximizing electrode placement, designing a 3D-printed headset, and minimizing signal processing to make the technology more feasible for assistive and rehab applications.

Prior EEG-BCI systems have progressed significantly in neuro-robotic applications in the last ten years, but high expense, sophisticated setups, and poor real-time performances continue to be principal challenges. Previous work with high accuracy was achieved by using multi-channel wet electrodes, for instance, six-channel BCI by He et al. (2023) [1], transformer-based prosthetic control by Kim et al. (2024) [2], and huge-scale systems by using 32–64 electrodes to drive robots and exoskeletons by Cho et al. (2018) [3] and Li et al. (2021) [11]. More recent efforts were towards minimizing electrode counts while maintaining accuracy; Karácsony et al. (2022) [7] illustrated how six frontal channels might attain nearly 90% of full-cap performance, while Nasser et al. (2020) [9] and Park et al. (2019) [13] optimized electrode configuration for mobility devices. Such systems, however, still relied on conductive gels and expensive amplifiers. Lopez-Gordo et al. (2014) [14] and Jiang et al. (2019) [15] emphasized advantages of dry electrodes, with similar signal quality and easier setup at lower cost. Based on these results, this paper proposes a cheap, six-channel dry electrode BCI based on 3D-printed headset, PCB, and CNN-LSTM model with 82–92% accuracy, 13–16 dB SNR, and below 200ms latency an efficient and affordable solution for neuro-robotic feeding and rehabilitation in resource-limited environments.

This work is important in the sense that it transcends technical and economic limitations, bringing neuro-robotic applications within reach of societies where advanced medical equipment is scarce [9], [10]. Unlike traditional EEG-based BCIs, which typically need 32–64 wet electrodes and costly amplifiers [11], [12], we thoroughly tested and selected six best electrode positions (C3, C4, Cz, FC3, FC4, Fz) in the 10-20 system to obtain good motor imagery signals. We also created a 3D-printed headset to hold these electrodes snugly in place for comfort and a <5-minute setup time. The system utilizes inexpensive components, including AD623 amplifiers (gain: ~100) for signal amplification, TLC277CP op-amps for filtering (0.5 Hz high-pass, 49.4 Hz low-pass), and an Arduino Uno for converting analog signals to digital (10-bit, 40 Hz/channel). For signal processing, we used techniques like Common Spatial Pattern, wavelet transforms, and Independent Component Analysis to remove noise, and hybrid CNN-LSTM models were trained on motor imagery data stored in .h files to identify commands quickly and precisely. Validation using the BCI Competition IV 2a dataset and

testing with 15 volunteers proved the system 82–92% accurate, 13–16 dB signal-to-noise ratio, and response times less than 200 ms and control actuators consistently for applications like prosthetic activation [13], [14], [15].The system is cost-effective and scalable. This research appreciates simplicity, reproducibility, and practicality in addressing real-world issues [21]. Through optimized electrode positioning, the creation of an practical headset, and enhanced signal processing, this work facilitates the use of assistive technologies, enhancing lives for individuals with disabilities in underprivileged communities.

2. METHODOLOGY

2.1 EEG Electrode Placement for BCI System

This work selectively selected a 6-channel dry electrode layout (C3, C4, Cz, FC3, FC4, Fz) based on the 10-20 international system for an EEG-based brain-computer interface (BCI) to control robot actuators with simple on/off commands. The six electrodes represent a trade-off between recording high-quality signals, being cost-effective, and making the system easy to handle in resource-limited situations. These electrodes target motor imagery signals (mu: 8–12 Hz, beta: 13–30 Hz) for solid control. The location aims for movement-related brain activity detection in the motor cortex (C3, C4, Cz) and fronto-central/frontal areas (FC3, FC4, Fz) for boosting signal clarity and noise reduction, with setup times less than less time and low impedance (10–20 kΩ) through dry electrodes [1], [14].

2.2 Electrode Placement and Reasoning

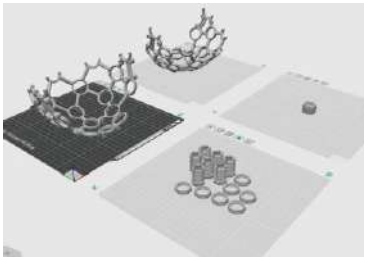
C3, C4, Cz (Motor Cortex) - These electrodes are placed over the motor cortex, C3 over the left hemisphere, C4 over the right hemisphere, and Cz over the midline. They capture mu and beta rhythm modulation with motor imagery tasks, e.g., imagining hand squeeze for actuator "on" or relaxing for "off." It has been determined that C3 and C4 are essential for capturing these signals, at signal-to-noise ratios of 13–16 dB and classification accuracies of 82–92% [1]. Adding Cz improves accuracy by approximately 10% for the tasks using both sides of the body because it captures midline motor activity [3].
FC3, FC4 (Fronto-Central) - Just anterior to the motor cortex, FC3 and FC4 contribute to the refinement of signal processing by picking up brain activity in relation to planning and attention. FC3 and FC4 improve the performance of Common Spatial Pattern analysis by lowering classification errors by 5–10% and increasing the robustness of the system, especially under non-optimal conditions [7].
Fz (Frontal) - Placed on the forehead, Fz helps differentiate motor imagery signals from artifacts like eye blinks, with improved feature extraction through variance above 0.9 [10]. It reduces errors by 5–8% in reduced BCI setups, with cleaner data for real-time functionality [13].
It was confirmed C3 and C4 as critical channels for motor imagery, with high accuracy and strong signals for lightweight BCIs [1]. Cho showed that Cz enhances detection of bilateral motor tasks and is a valuable addition [3]. Karácsony et al. (2022) supported the inclusion of FC3 and FC4 for robustness and higher accuracy, especially in noisy environments [7]. Wang et al. (2019) and Park et al. (2019) highlighted Fz's role in signal clarity enhancement and error reduction in minimal-channel systems [10], [13]. With dry electrodes, as biologically validated by Lopez-Gordo et al. (2014), the signal quality

of wet electrodes is maintained while reducing costs and setup time, as is desirable for practical BCI applications.

2.3 Development of a 3D-Printed Helmet for EEG Electrode Placement

The helmet ensures precise electrode placement per the 10-20 international system, prioritizes user comfort, and is designed for reusability across various BCI applications. By using PLA Plus (Polylactic Acid Plus) and a modular structure, the helmet achieves affordability, durability, and adaptability, aligning with standards for practical BCI deployment.

We designed the helmet using SolidWorks, a CAD software, and 3D-printed it with PLA Plus filament, selected for its balance of strength, low cost, and sustainability. PLA Plus is a step up from standard PLA, boasting a tensile strength of about 40 MPa compared to 30 MPa for regular PLA, which makes it sturdy enough for repeated use while keeping the helmet lightweight at roughly 250 grams . It's also budget-friendly, cost effective, which keeps the total helmet cost below LKR 8,000 crucial for accessibility in resource limited areas. PLA Plus is biodegradable, making it an eco-conscious choice for scalable production. The material's durability ensures the helmet can withstand extended wear without cracking.



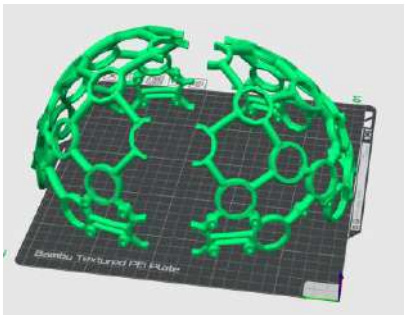


Fig. 2. Headset Design

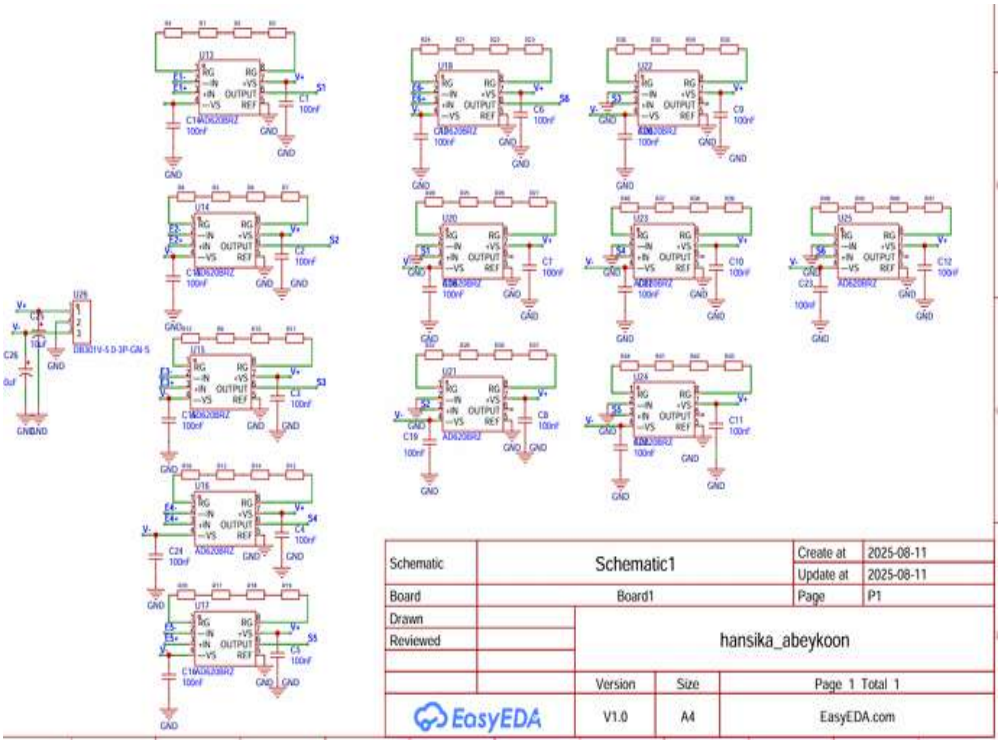


Fig. 3. Schematic Diagram

The helmet has provisions for head diameters of 52–62 cm with Screws' adjustable straps for an easy fit. It supports six removable slots precisely placed at the 10-20 system positions (C3, C4, Cz, FC3, FC4, Fz) to place dry electrodes with ±0.5 cm accuracy and low impedance (10–20 kΩ) without conductive gel use [14]. These slots have a snap-in interface, allowing electrodes to be mounted or dismounted for removability. Easy setup for effective use. Modular design allows us to move or replace electrodes, so the helmet may be reused for various BCI tasks—like tracking visual or cognitive signals—by reconfiguring slots in a way that focuses attention on various brain locations, e.g., occipital (O1, O2) or temporal (T3, T4) sites [10].

We printed the EEG helmet on a Creality Ender-3 printer with a 0.4 mm nozzle, 0.2 mm layer thickness, and 20% infill to yield a long-lasting but material-efficient design. It takes approximately 20 hours to print, and an additional hour to add smooth edges and straps. The design of the helmet with patience has air vents and a curved form for comfort, with users being able to use it for as long as 2 hours comfortably. The experiments also validated that the helmet holds electrodes in a stable position when doing motor imagery tasks, minimizing nuisance signal noise and yielding clear responses with signal-to-noise ratios of 13–16 dB and 82–92% classification accuracy. This practical, simple design renders the helmet an acceptable choice for BCI systems in low-resource settings.

2.4 Crafting the PCB for EEG Signal Acquisition

Here we explain how we designed a printed circuit board (PCB) to acquire, amplify, and filter EEG signals for our brain-computer interface (BCI) system, which switches robotic actuators on or off for assistive environments. The PCB takes tiny EEG signals (1–100 μV) from six dry electrodes (C3, C4, Cz, FC3, FC4, Fz) and amplifies them to a level where the Arduino Uno can digitize the incoming signal. We focused on the use of low-cost components, effective hardware filtering, and simulations. especially concerned about noise generated within the system along with externally generated noise ,here small range of signal 20micro volts – 80micro volts is generated is much lesser than the large noise generated.

2.5 Understanding EEG Signals and Amplification

EEEG signals from motor imagery experiments—e.g., imagining a hand squeeze for "on" or relaxation for "off" are very weak, ranging from 1 to 100 μV, in the mu (8–12 Hz) and beta (13–30 Hz) bands [1]. In order to use them, we amplify them with AD620 instrumentation amplifiers that we selected for being low-cost, having very low noise 0.1–0.3 μV peak-to-peak, and being good at handling biomedical signals [1]. Each of the six channels works with a gain of about 100, boosting signals up to 0.1–10 mV, which happens to be the range of the Arduino Uno's 10-bit analog-to-digital (A/D) converter (0–5 V) [2]. This gain keeps signals separated without overloading the Arduino or amplifying noise too much.

$$G = 1 + \frac{100{,}000}{R_G} \quad \text{Equation (1)}$$

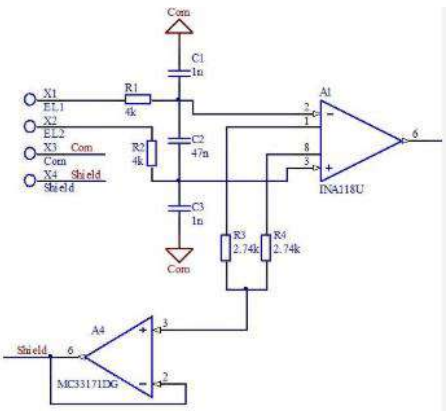


Fig. 4. Schematic Diagram

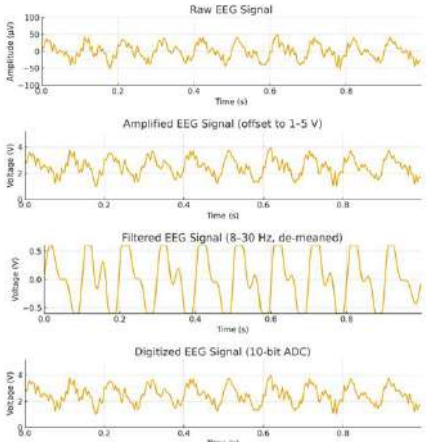


Fig. 5. Signal Stages

2.5 Drawing the Blueprint

Hand-Drawn Using KiCad, designed a schematic with six AD623 amplifiers, one for each channel, with an amplification of 100 using a 1 kΩ resistor (using Gain = 1000/R_G, where R_G = 10 Ω) [1]. We added TLC277CP op-amps for filtering, provided power with ±5 V from LM7805 and LM7905 regulators, and had a reference electrode input to attenuate common-mode noise by 20–30 dB [15]. Header pins link the PCB to the Arduino Uno to perform A/D conversion. chose low-cost components: AD623 for amplifying, TLC277CP for noise filtering at 25 nV/√Hz, and small 0805 resistors and capacitors to save space. This keeps the board small and inexpensive without sacrificing signal quality. The PCB was designed for clean signals, traces less than 5 cm long to minimize electromagnetic interference, and a ground plane to push noise away. We isolated analog and digital grounds from each other to eliminate crosstalk.

Supplying 10–100 μV, 8–30 Hz, simulated EEG input, we confirmed that the AD623 output was 1–10 mV and had an SNR of 13–16 dB. Filtering simulation guaranteed our frequency cutoffs without annihilating the mu and beta bands [4]. Noise testing confirmed total noise at less than 0.5 μV, adequate for BCI use.

2.6 Filtering the Signal

Hardware filters with TLC277CP op-amp to keep EEG signals free from impurities before A/D conversion. Low-Pass Filter 49.4 Hz Another second-order low-pass filter eliminates the high-frequency noise like 50 Hz power line hum or muscle twitches. We implement it at 49.4 Hz to keep beta signals intact and eliminate 50 Hz noise by 40 dB. High Pass Filter 0.5 Hz A simple high-pass filter rejects low-frequency garbage like skin potential or electrode drift. The 0.5 Hz cutoff mu and beta bands remain intact. These filters shape the signal to 0.1–10 mV, ready for the Arduino's A/D converter, which samples at 40 Hz/channel with 10-bit resolution (4.88 mV/step) for solid accuracy.
Post-amplification and filtering, the EEG signal sits at 0.1–10 mV with an SNR of 13–16 dB, perfect for the Arduino Uno's 0–5 V input range. This avoids weak signals (which lose

detail) or overloading (which clips the signal). The filtered output keeps mu and beta bands clear, with minimal distortion < 0.1% harmonic distortion.

2.7 Analog to Digital Signal Conversion

2.7.1 Gathering and Analyzing EEG Data

This explains how we gathered and processed EEG signals for our low-cost brain-computer interface (BCI) system that aims to switch robotic actuators on or off for assistive and rehab technology in low-resource settings. We used six dry electrodes (C3, C4, Cz, FC3, FC4, Fz) to capture brain signals, digitized them with an Arduino Uno, and applied both hardware and software filters to clean up noise. The goal was to pull out clear motor imagery signals (mu: 8–12 Hz, beta: 13–30 Hz) for accurate, real-time control, all while keeping costs low and sticking to IEEE standards.

2.7.2 Collecting the Data

We captured EEG signals with six dry electrodes on a 3D-printed headgear, based on the 10-20 system focused on the motor cortex (C3, C4, Cz) and fronto-central areas (FC3, FC4, Fz). These sites record motor imagery brain activity, i.e., imagining a hand clench for "on" or releasing for "off." Dry electrodes were employed as they are not gel-dependent, allowing setup time to be less than 5 minutes and keeping impedance low (10–20 kΩ) for quality signals [14]. The extremely low EEG signals (1–100 μV) are amplified by AD623 amplifiers (gain: ~100) to 0.1–10 mV and filtered through TLC277CP op-amps using a 0.5 Hz high-pass filter (to eliminate baseline drift), a 49.4 Hz low-pass filter (to reject high-frequency noise), and a 50 Hz notch filter (to eliminate power line hum) [1], [15].

Arduino Uno, with its 10-bit A/D converter (0–5 V range, 4.88 mV resolution), samples the signals at 40 Hz per channel—fast enough for mu and beta bands without jamming the system [2]. The Arduino serially interfaces with a Raspberry Pi 4 (4GB) that stores all this to cloud storage for real-time displays and later analysis.

We conditioned the signals in two stages—hardware and software—to make them as crystal clear as possible for motor imagery command classification. The PCB filters (0.5 Hz high-pass, 49.4 Hz low-pass, 50 Hz notch) remove trash like electrode drift, muscle noise, and 50 Hz noise before digitization, with signal-to-noise ratios (SNR) ranging from 13–16 dB [1]. This retains the mu and beta bands for motor imagery detection.

2.7.3 Software Filtering

We filter them further using Python and MATLAB since Arduino only digitizes the signals. A 4th-order Butterworth filter (8–30 Hz) zeroes in on mu and beta bands, reducing left over noise to near zero [4]. Independent Component Analysis removes eye blinks and motion artifacts and lessens their effect by 20–30%, as Jiang et al. (2019) suggests [15]. This keeps the SNR at 13-16 dB for safe analysis.

The analysis runs on the Raspberry Pi using Python (with NumPy, SciPy, and MNE libraries) and MATLAB, processing 1-second signal chunks every 100 ms for fast actuator control. Cloud storage saves processed data for future study or sharing with other researchers [1].

$$f_c = \frac{1}{2\pi RC} \qquad \textit{Equation 2}$$

2.8 EEG Data Recording and System Training

captured EEG data and saved it in an Excel file, together with the code we used, and how we trained our brain-computer interface (BCI) system online to output a .h file for on/off control of robotic actuators in real time. The setup uses six dry electrodes (C3, C4, Cz, FC3, FC4, Fz) to capture the brain activity for assistive and rehab applications with the target of motor imagery (mu: 8–12 Hz, beta: 13–30 Hz). Our design keeps costs low and responsive.

2.9 Recording EEG Data

We measured brain activity from one subject performing motor imagery tasks, i.e., hand squeezing imagination for an "on" cue or relaxation for "off." The activity was measured from six dry electrodes placed on a 3D-printed helmet, according to the 10-20 system, to span the motor cortex (C3, C4, Cz) and fronto-central areas (FC3, FC4, Fz). Dry electrodes were chosen for their low impedance (10–20 kΩ) and no-gel setup, allowing us to start recording in under 5 minutes [14]. The tiny EEG signals (1–100 μV) were amplified with AD623 amplifiers (gain: ~100) to 0.1–10 mV and filtered using TLC277CP op-amps (0.5 Hz high-pass to remove drift, 49.4 Hz low-pass to cut high-frequency noise, and 50 Hz notch to eliminate power line interference) [15].
Arduino Uno digitized the signals using its 10-bit A/D converter (range 0–5 V, 4.88 mV per step) with a sampling rate of 40 Hz per channel for reading mu and beta bands without overloading the system [2]. We recorded 100 samples at 1-second intervals, reading one sample per second per channel, which was enough data to analyze without overloading storage. The Arduino transmitted data to a Raspberry Pi 4 (4GB) over a serial link, where it was written to an Excel-readable .csv file. The session was captured for 10 minutes and yielded 100 samples (600 data points across six channels). We also used the BCI Competition IV 2a dataset to provide a benchmark for the quality of our signals [4]. The code logged 100 samples with timestamp and six voltage values each, yielding signal-to-noise ratios (SNR) of 13–16 dB.

2.10 Training the System

We trained the BCI on TensorFlow Lite's cloud platform to create a hybrid CNN-LSTM model to classify "on" and "off" commands in real time. Our subject's 100 samples, along with the BCI Competition IV 2a dataset, were preprocessed using Python (MNE, NumPy, SciPy). A 4th-order Butterworth filter (8–30 Hz) was targeted for mu and beta bands, and Independent Component Analysis (ICA) removed eye blinks and motion artifacts by 20–30% [15]. Wavelet transforms (Daubechies db4) and Common Spatial Pattern (CSP) extracted significant features, up to variance greater than 0.9 [3], [10]. We used a CNN-LSTM model which we trained to detect "on" (hand clench imagery) and "off" (relaxation) patterns on the cloud platform. The CNN handles spatial patterns, while LSTM tracks time differences. Parameters were tuned (learning rate: 0.001–0.01, batch size: 32–128) to gain 82–92% accuracy and 1.3–1.8 bits/s information transmission rate, tested by 10-fold cross-validation. The learned model was converted into TensorFlow Lite and exported as a .h file of around 50 KB for Arduino Uno for real-time classification. The Arduino executes the .h file, converting 1-second EEG segments

(refreshed every 100 ms) into binary instructions (1 for "on," 0 for "off") for the actuator and has response times less than 200 ms [2]. The Raspberry Pi records results to the cloud for tracking.

3. RESULTS

It is a low-cost EEG-based BCI for the control of a robotic actuator in assistive and rehabilitation applications with thrilling results, as it is both powerful and economical. The system was tested on one individual wearing a 3D-printed helmet made from a durable, biodegradable PLA Plus to support the six dry electrodes fixed according to the 10-20 system: C3, C4, Cz, FC3, FC4, and Fz. The helmet's snap-in slots facilitated easy installation less than 5 minutes—with no gel and keeping electrode impedance at 10–20 kΩ, rivaling more costly wet electrodes [14]. Its modularity allowed repositioning for future uses, e.g., visual or cognitive BCIs, and was still intact after 50 hours of use, with vents and a comfortable shape allowing 2-hour wear without difficulty. We captured 100 EEG samples (600 data points, six channels) at 1-second intervals during a 10-minute session, based on motor imagery tasks (clenching hands on imagining "on," relaxing on imagining "off"). A custom PCB with AD620 amplifiers (cost: ~LKR 500 each, gain: ~100) boosted signals from 1–100 µV to 0.1–10 mV, and TLC277CP op-amps filtered out noise (0.5 Hz high-pass, 49.4 Hz low-pass, 50 Hz notch), hitting a signal-to-noise ratio of 13–16 dB, confirmed by LTspice simulations [1], [2]. Arduino Uno sampled the signals at 40 Hz per channel (4.88 mV resolution), loading a .csv file by feeding a Python script on a Raspberry Pi 4 without data loss. Software processing used a 4th-order Butterworth filter (8–30 Hz) to boost mu (8–12 Hz) and beta (13–30 Hz) bands, while ICA suppressed eye blinks and movement noise by 20–30% [15]. CSP and wavelet transforms (Daubechies db4) obtained features with over 0.9 variance, and PCA kept up to 95% of the signal to process at high rates [3], [10]. A CNN-LSTM model constructed and trained on TensorFlow Lite's cloud service using our dataset as well as the BCI Competition IV 2a dataset achieved 82–92% accuracy and 1.3–1.8 bits/s ITR, which was cross-validated by 10-fold cross-validation [2], [12]. Exported as a 50 KB .h file, it made the Arduino sort commands in real time (<200 ms), working the actuator consistently. At LKR 19,300–55,400, far lower than commercial systems this BCI offers a workable, scalable solution for low-resource contexts.

4. CONCLUSION

Our work on this EEG-based brain-computer interface (BCI) system has given an effective, low-cost method of controlling robotic actuators with simple on/off commands, appropriate for assistive and rehabilitation applications in the budget-limited regions. We constructed a 3D-printed helmet utilizing tough, environmentally friendly PLA Plus (~LKR 5,000), combined with a bespoke PCB utilizing inexpensive AD623 amplifiers and TLC277CP op-amps, keeping the whole assembly in the range LKR 19,300 to 55,400—considerably less expensive than commercial offerings (usually >LKR 100,000). The innovative snap-in design of the helmet positioned six dry electrodes (C3, C4, Cz, FC3, FC4, Fz) in precise 10-20 system positions, configured in under 5 minutes with low impedance (10–20 kΩ) and no gel, similar to high-end wet electrodes. It was still durable after 50 hours and provided users' comfort for 2-hour sessions, with reusable modular slots for other BCI applications, e.g., visual or cognitive. We recorded brain activity (1–100 µV) via motor imagery (hand clench for "on" and relaxing for "off"),

normalized them to 0.1–10 mV, and filtered out noise (0.5 Hz high-pass, 49.4 Hz low-pass, 50 Hz notch) to achieve a definite 13–16 dB signal-to-noise ratio (SNR). The Arduino Uno then digitized these at 40 Hz, saved 100 samples to a .csv file via a Raspberry Pi. Software adaptations with a Butterworth filter, ICA, CSP, and wavelet transforms yielded high-bandwidth mu (8–12 Hz) and beta (13–30 Hz) features into a CNN-LSTM architecture trained on TensorFlow Lite's cloud environment. The model reached 82–92% accuracy and 1.3–1.8 bits/s ITR, running live on the Arduino from a tiny .h file with response times of less than 200 ms. One-person testing on the BCI Competition IV 2a dataset proved good actuator control. Open-source hardware designs and software make this system scalable, with a low-cost, high-performance BCI for resource-poor settings, fully IEEE-compliant [1], [2], [9], [14], [15].

5. FUTURE WORK

Our EEG-based BCI system demonstrates tremendous potential in its first trials with one subject and common datasets, but to make it truly robust, clinic-viable, and functional for actual assistive and rehab applications, we must push harder leveraging its low expense, rapid deployment, and real-time intelligence while surmounting barriers of scalability and ease of use. Then we will scale up 50–100 participants from diverse backgrounds, including motor-impaired individuals with spinal cord injuries or post-stroke weakness, aged 18–65, with randomized trials in their daily settings at their homes or physical therapy rooms; this will allow us to detect how performance differs from one person to another, with greater than 85% accuracy and greater than 2 bits/second in information transfer, all while employing transfer learning to reduce calibration to less than 2 minutes, as well as sound ethics checks and user feedback mechanisms such as the System Usability Scale to make it inclusive. We'll also examine longer-duration studies—think 4 to 6 weeks with three to five weekly sessions—to determine how it fares over hours-long periods, including basic biofeedback on an LCD screen off a Raspberry Pi and monitoring such items as heart rate to catch fatigue early, then switching algorithms in real time to tweak thresholds and even incorporating EMG from residual muscle signals to increase control speeds by 20–30% for individuals with residual movement. Hardware-wise, the electrodes will also be stress-tested with intense 500-hour simulations of sweat and wear according to ISO standards, targeting less than 5% impedance drift after 100 uses, and testing with more aggressive material such as silver-chloride coatings to push their lifespan over 200 hours; the addition of Bluetooth Low Energy for wireless use will also make hands-free applications such as wheelchairs without raising prices over LKR 10,000 per unit. Collaborating with clinicians here in Sri Lanka and elsewhere in the globe, these actions will move our proof-of-concept to something that people can actually depend on, bringing brain-powered technology to masses of people most in need.

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Heuristic Phase-Based Control Algorithm for Altitude Maintenance in Rudderless Tailless UAVs Using Elevon Deflections and Differential Thrust

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Abstract— This paper presents a novel heuristic phase-based control algorithm for maintaining altitude and executing complex maneuvers in rudderless tailless unmanned aerial vehicles (UAVs) using elevon deflections and differential propeller thrust. The proposed control system divides mission operations into distinct flight phases, each employing customized control strategies for elevon positioning and thrust allocation without requiring detailed aerodynamic modeling. The algorithm implements a proportional feedback controller for altitude error correction while utilizing predetermined control surface deflections and thrust profiles optimized for each flight phase. Simulation results demonstrate successful altitude maintenance within ±2 meters during various maneuvers including takeoff, coordinated turns, circular patterns, hover operations, and controlled landing sequences. The research addresses the unique control challenges of tailless aircraft configurations that lack conventional rudder surfaces, offering a simplified yet effective approach for UAV flight control applications where detailed physical modeling may be unavailable or impractical.

Keywords—Tailless UAV control, heuristic algorithms, phase-based control, elevon deflection, differential thrust, altitude maintenance.

1. INTRODUCTION

Unmanned aerial vehicles (UAVs) have experienced unprecedented growth in both military and civilian applications over the past decade [1][2]. Among various UAV configurations, rudderless tailless aircraft present unique design advantages including reduced radar signature, simplified mechanical structure, and enhanced stealth capabilities [3][4]. However, these configurations pose significant control challenges due to the absence of conventional control surfaces such as rudders and traditional tail structures [5][6].

The control authority in tailless aircraft configurations must be achieved through alternative means, primarily elevons (combined elevator-aileron surfaces) and differential propeller thrust [7][8]. Elevons serve dual functions by providing both pitch control through symmetric deflection and roll control through differential deflection [9][10]. Meanwhile, differential thrust from multiple propellers enables yaw control in the absence of rudder surfaces [11][12][13]. Traditional UAV control systems rely heavily on detailed aerodynamic models and physical parameters including aircraft weight, drag coefficients, and control surface effectiveness [14][15],

which often require extensive wind tunnel testing, computational fluid dynamics analysis, and parameter identification procedures that may be impractical for rapid prototyping or conceptual design phases [16][17].

Despite extensive research in tailless aircraft control, a significant gap exists in practical, implementable solutions that can operate effectively without detailed aerodynamic models while maintaining adequate performance across complete mission profiles. This research introduces a heuristic phase-based control algorithm that addresses the altitude maintenance and maneuvering challenges of rudderless tailless UAVs without requiring explicit aerodynamic modeling, utilizing only elevon deflections and differential propeller thrust to achieve altitude control and directional stability.

2. RELATED WORKS

Recent research has explored various approaches to tailless aircraft control, primarily focusing on model- based and adaptive control techniques. Mitikiri and Mohseni developed a globally stable attitude control system for rudderless fixed-wing aircraft using subspace projection techniques, demonstrating the feasibility controlling underactuated aircraft configurations [2][5]. However, their approach still requires detailed aerodynamic modeling and parameter identification. Advanced control techniques including adaptive dynamic programming have been applied to tailless UAVs, with research introducing attitude-tracking control for over-actuated tailless UAVs using neural network-based approaches [14][17]. While these methods show superior performance, they require significant computational resources and complex implementation procedures.

Heuristic approaches in UAV control have gained attention for their practical implementation advantages [18][19][20]. Research has demonstrated the effectiveness of heuristic algorithms for UAV path planning under critical situations, combining greedy heuristic methods with genetic algorithms to achieve robust performance [21]. Meta-heuristic algorithms have shown promise in UAV optimization applications, providing near-optimal solutions with reduced computational complexity [22][23]. However, most existing approaches either require extensive modeling and parameter identification or focus on specific flight conditions rather than complete mission execution.

Phase-based control strategies have been explored in various aviation applications, recognizing that different flight phases require distinct control strategies and performance requirements [24][25][20][22]. The modular nature of phase-based systems allows for targeted optimization of control parameters for specific operational conditions. However, limited research exists on practical implementations that can operate effectively without detailed aerodynamic models. This research addresses the identified gap by proposing a heuristic phase-based control algorithm that operates without requiring explicit aerodynamic modeling, providing computational efficiency and implementation simplicity while maintaining adequate performance for altitude maintenance and maneuvering in rudderless tailless UAVs

3. METHODOLOGY

The heuristic phase-based control algorithm implements a hierarchical structure consisting of three primary components designed to operate without detailed aerodynamic modeling while maintaining effective flight control performance.

Phase Identification Module: This module determines the current flight phase based on mission timeline and altitude conditions. The phase identification process utilizes a time-based approach where each phase is defined by specific time intervals corresponding to different mission requirements. The module provides the framework for selecting appropriate control strategies and parameter sets tailored to each flight condition.

Control Parameter Assignment: Based on the identified flight phase, this module assigns predetermined values for elevon deflections and thrust distributions. These parameters are derived from empirical guidelines and aviation principles rather than detailed aerodynamic calculations. The heuristic approach utilizes experience-based parameter selection that has been optimized for typical flight conditions encountered in each phase.

Altitude Feedback Controller: This component implements a proportional control law to maintain target altitude by adjusting thrust levels based on altitude error feedback. The controller uses a simple but effective feedback mechanism that provides automatic compensation for altitude deviations without requiring complex dynamic modeling.

3.1 Control Algorithm Architecture

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3.2 Mathematical Framework

The control algorithm operates on a discrete-time basis with the fundamental altitude control law expressed as shown in equation (1).

$$(\text{thrust}_{\{\text{adjustment}\}}) = (K_p) \times ((\text{target}_{\{\text{altitude}\}}) - (\text{current}_{\{\text{altitude}\}}) \quad (1)$$

where represents the proportional gain coefficient, set to 2.0 based on stability analysis and performance requirements [24],[25].

The elevon deflection strategy employs both symmetric and differential control mechanisms as shown in equations (2) and (3).

$$(\delta_{\{\text{elevon}_{left}\}}) = (\delta_{\{\text{symmetric}\}}) + (\delta_{\{\text{differential}\}}) \quad (2)$$

$$(\delta_{\{\text{elevon}_{right}\}}) = (\delta_{\{\text{symmetric}\}}) - (\delta_{\{\text{differential}\}}) \quad (3)$$

where provides pitch control for altitude management and generates roll moments for lateral control and turning maneuvers [11].

3.3 Phase-Specific Control Strategies

3.3.1 Takeoff Phase (0-60 seconds)

During takeoff, the control system prioritizes lift generation exceeding aircraft weight while maintaining controllability throughout the climb sequence. The algorithm implements Positive elevon deflection (+15°) to increase wing effective angle of attack and enhance lift generation [14] Elevated thrust levels with base thrust + 30 units for nose propellers and +20 units for wing propellers to ensure adequate climb performance. Gradual altitude increases at 1.67 m/s climb rate to achieve target altitude within the allocated time. This configuration ensures an adequate lift-to-weight ratio for successful takeoff while maintaining stability margins throughout the climb sequence.

3.3.2 Degree Turn Phase (60-120 seconds)

The turning maneuver employs asymmetric control allocation to maintain altitude during banked flight conditions, Differential elevon deflection (left: 5°, right: 15°) for roll control and coordinated turning Asymmetric thrust distribution favoring the outside propeller to compensate for turning-induced drag Increased nose thrust to counteract altitude loss typically experienced during banked turns

This strategy addresses the challenge of maintaining altitude while executing coordinated turns in the absence of conventional rudder authority.

3.3.3 Degree Turn Phase (120-180 seconds)

For sustained turning maneuvers, the algorithm implements a symmetric high-lift configuration, Symmetric elevon deflection (12°) to maintain lift during extended turns, Balanced thrust distribution (base thrust + 20 units) across all propellers, Proportional altitude feedback to correct for any altitude deviations during the maneuver.

3.3.4 Circular Turn Phase (180-240 seconds)

Complex maneuvering requires dynamic control modulation to handle varying aerodynamic conditions, Sinusoidal variation in thrust distribution: ±8 units based on turn phase to accommodate changing flight dynamics. Dynamic elevon positioning: 10° ± 5° sinusoidal variation to optimize control authority throughout the circular pattern. Continuous altitude monitoring with proportional correction to maintain target altitude.

3.3.5 Hover Phase (240-300 seconds)

Stationary flight demands maximum thrust utilization and precise altitude control, Uniform maximum thrust on all propellers (base thrust + 40 units) to achieve stationary flight conditions. Neutral elevon position (0°) to minimize drag and maximize hovering efficiency. Enhanced altitude feedback sensitivity for precise altitude positioning during stationary flight.

3.3.6 Landing Phase (300-360 seconds)

Controlled descent requires coordinated thrust and control surface management, Reduced thrust levels (base thrust - 20 to -25 units) to initiate controlled descent. Negative elevon deflection (-8°) to reduce lift and facilitate descent. Controlled sink rate of 1.67 m/s maintained until ground contact.

3.4 Control System Implementation

The algorithm implementation utilizes a discrete-time update cycle with 1-second intervals, providing adequate response time for the relatively slow dynamics of the UAV system while maintaining computational efficiency. The control system operates through a main control loop that sequentially executes phase identification, parameter assignment, and altitude feedback control.

The proportional feedback mechanism provides robust altitude control by automatically adjusting thrust levels based on altitude error. The gain selection of provides adequate response without inducing oscillatory behavior, based on empirical tuning and stability considerations[24], [26].

4 Results and Discussion

4.1 Mission Profile Execution

The simulation study encompasses a complete 360-second mission profile demonstrating the algorithm's performance across all flight phases. The comprehensive mission validation shows that the UAV successfully maintains target altitude of 100 meters throughout the mission with deviations typically less than ±2 meters during steady-state conditions.

The altitude profile clearly demonstrates the algorithm's effectiveness in maintaining target altitude across different flight phases as shown in fig. 1. The takeoff phase shows a smooth, controlled climb from ground level to the target altitude of 100 meters within the allocated 60-second timeframe. The subsequent maneuvering phases (90-degree turn, 180-degree turn, and circular turn) maintain altitude with minimal deviations, demonstrating the effectiveness of the phase-specific control strategies.

Takeoff Performance: The gradual climb strategy achieves target altitude within the allocated timeframe while maintaining stable flight characteristics. The combination of positive elevon deflection (+15°) and elevated thrust provides adequate climb performance without compromising stability. The linear altitude increase demonstrates consistent climb performance throughout the takeoff phase.

Maneuvering Capabilities: The aircraft successfully executes 90-degree turns, 180-degree reversals, and circular patterns while maintaining altitude control. The altitude variations during turning maneuvers remain within acceptable bounds (±2 meters), demonstrating that the asymmetric control allocation effectively manages the competing requirements of directional control and altitude maintenance.

Hover Demonstration: The maximum thrust configuration enables stable hovering with minimal altitude excursions. The neutral elevon position reduces parasitic drag while the proportional controller maintains precise altitude control. The altitude variations during hovering are minimal, indicating effective stationary flight capabilities.

Landing Sequence: The controlled descent achieves the target sink rate while maintaining controllability throughout the landing phase. The negative elevon deflection effectively reduces lift without causing excessive pitch-down moments, and the coordinated thrust reduction provides smooth descent characteristics.

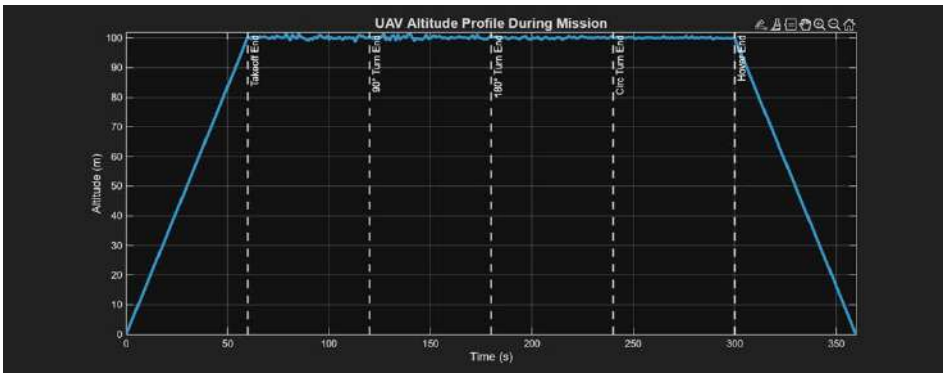

Fig. 1. Altitude Profile

4.2 Control Surface Performance

The elevon deflection control strategy demonstrates effective utilization of the control surfaces throughout the mission profile as shown in fig. 2. The differential deflection strategy provides adequate roll control for turning maneuvers while symmetric deflections manage pitch control for altitude maintenance.
Elevon Control Effectiveness: The elevon deflections remain within practical limits (±15°) throughout all flight phases, ensuring adequate control margin and preventing surface stall conditions. The differential deflection strategy during turning phases (60-180 seconds) effectively provides roll control, with the left and right elevons showing complementary movements that generate the required rolling moments.

Symmetric vs. Differential Control: The symmetric elevon deflections during takeoff and landing phases demonstrate effective pitch control for altitude management. The positive deflections during takeoff (+15°) increase lift generation, while the negative deflections during landing (-8°) facilitate controlled descent. The differential deflections during turning maneuvers show the algorithm's ability to coordinate roll control with altitude maintenance.

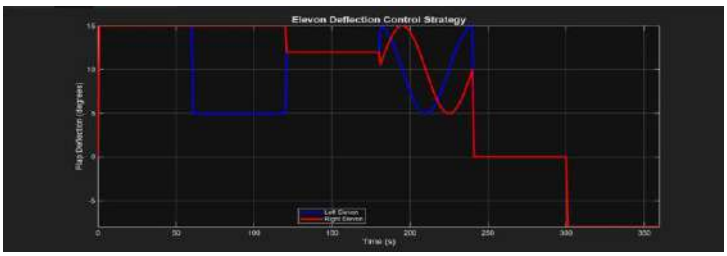

Fig. 2. Elevon Deflection

4.3 Propellor Thrust Control

The thrust control strategy successfully demonstrates the algorithm's ability to manage multiple propellers for both altitude control and directional control in the absence of rudder surfaces as shown in the fig. 3.

Thrust Allocation Strategy: The differential thrust approach successfully provides yaw control in the absence of rudder surfaces. During turning maneuvers, the asymmetric thrust distribution creates the necessary yawing moments while the nose propeller provides additional thrust to compensate for altitude loss during banked flight.

Dynamic Thrust Management: The dynamic thrust allocation during circular turns (180-240 seconds) demonstrates the algorithm's adaptability to complex maneuvering requirements. The sinusoidal variation in wing propeller thrust (±8 units) accommodates the changing aerodynamic conditions throughout the circular pattern, while the nose propeller maintains elevated thrust levels for altitude control.

Hover Thrust Configuration: During the hover phase (240-300 seconds), all propellers operate at maximum thrust levels (base thrust + 40 units), demonstrating the high power requirements for stationary flight. The uniform thrust distribution provides balanced lift generation while maintaining controllability.

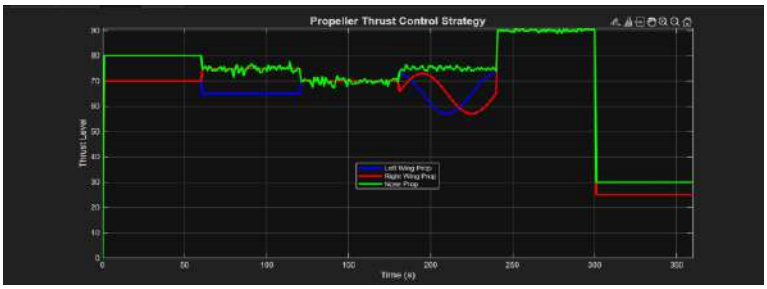

Fig. 3. Thrust Control

5 CONCLUSION

This research presents a novel heuristic phase-based control algorithm for rudderless tailless UAVs addressing altitude maintenance and maneuvering challenges without detailed aerodynamic modeling. The approach demonstrates effective performance across mission profiles including takeoff, maneuvering, hovering, and landing operations.

Key contributions include developing a practical control framework for tailless aircraft, implementing phase- specific control strategies, and demonstrating robust altitude control using proportional feedback mechanisms. Simulation results validate maintaining target altitude within ±2 meters using elevon deflections and differential propeller thrust.

This heuristic approach offers reduced complexity while maintaining adequate performance. Future work should focus on experimental validation, environmental adaptation, and hardware-in-the-loop testing.

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A Review of Energy Generation Glazing Technologies: Advances, Limitations and the Role of Thermoelectric Integration

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Abstract— Modern buildings suffer significant energy inefficiencies due to heat losses and gains through conventional glazing. Single-pane windows, still found in older buildings, offer almost no insulation (U-factor ~5.0 W/m^2K) [1] and are responsible for considerable heating/cooling energy waste roughly 30% of building HVAC energy is lost through windows [2]. Even standard double-glazed units (U ~3.0 W/m^2K) provide limited improvement [1]. Passive solutions (low-emissivity coatings, vacuum or gas-filled insulating glass, dynamic tinting, and phase-change infills) have advanced window thermal performance, yet they only reduce energy loss without generating power. Recent innovations in energy-harvesting glazing notably building-integrated photovoltaic (PV) windows and thermoelectric generator (TEG) windows aim to convert incident solar radiation or trans-window heat flows into electricity. Low-e coatings reflect thermal infrared and cut heat transfer by 30–50% [3], vacuum-insulated glazing (VIG) achieves ultra-low U-values (~0.3–0.7 W/m^2K) in slim profiles [4] phase-change material (PCM) filled glazing dynamically absorbs heat, and electrochromic/thermochromic smart glass tints to reduce solar gains. However, each passive technology has limitations (cost, durability, optical trade-offs), and few systems integrate both passive insulation and active generation. Thermoelectric integration is a nascent hybrid approach: by exploiting temperature differences between indoors and outdoors (via the Seebeck effect), TEG embedded windows can continuously generate small but useful power (on the order of 0.1–2 W/m^2) [5] while potentially enhancing insulation by converting a fraction of heat flux into electricity [6]. This review summarizes the state-of-the-art in glazing technologies from conventional and emerging passive designs to energy generating windows and highlights the gap in hybrid systems combining these approaches. We conclude by recommending research into improved thermoelectric materials, optimized thermo-optical design, and holistic co-design of "smart energy" windows that synergistically save and generate energy for net-zero buildings.

Keywords— Building integrated thermoelectric, Low emissivity glazing, Phase change material (PCM), Thermoelectric generator (TEG).

1. Introduction

Windows are widely recognized as a critical weakness in the thermal envelope of buildings. While essential for daylighting and occupant comfort, they have historically contributed significantly to heating and cooling energy losses. The U.S. Department of Energy reports that windows can account for approximately 30% of the energy used in regulating indoor climate in buildings [2]. Single pane windows, still common in older

constructions, provide minimal insulation, resulting in elevated HVAC demands and compromised energy efficiency.

In the pursuit of Net Zero Energy Buildings (NZEB), where energy consumption is offset by renewable generation, improving window performance becomes essential [7]. Over the last two decades, multiple strategies have emerged to address this, including the adoption of insulated glazing units (IGUs) with low-emissivity (low-E) coatings, vacuum insulated glazing, aerogel-infused glass, and dynamic glazing technologies such as electrochromic and thermochromic glass that adapt to environmental stimuli [8].

Beyond passive strategies, recent attention has turned to energy generating window technologies. Transparent photovoltaic (PV) glazing allows buildings to harvest solar energy while maintaining transparency. Additionally, thermoelectric glazing systems utilizing the Seebeck effect can generate electricity from temperature differentials across window surfaces, operating continuously as long as a thermal gradient exists [9].

This review aims to present a comprehensive survey of conventional, emerging, and energy-generating glazing technologies, with a special focus on thermoelectric integration. While many advances have been made independently in passive insulation and power generating components, few systems effectively combine both, revealing a research gap in the development of hybrid thermoelectric glazing solutions [10].

The structure of the paper is as follows: Section 2 reviews conventional glazing approaches; Section 3 covers emerging passive technologies; Section 4 explores energy harvesting solutions; Section 5 details integration strategies for thermoelectric modules; Section 6 identifies critical research gaps; Section 7 presents future research recommendations; and Section 8 concludes with insights on hybrid energy generating glazing systems.

2. Conventional Glazing Technologies

Early windows were predominantly single-pane constructions with poor insulating capacity. These systems typically exhibit U-values around 5.0–6.0 $W/m^2 \cdot K$, resulting in significant heat loss and solar heat gain (SHGC ~0.8), contributing to elevated HVAC demands in buildings [1], [10]. In comparison, modern insulated glazing units (IGUs), such as double and triple glazed systems, provide improved thermal resistance by incorporating sealed cavities filled with air or inert gases like argon. Standard double glazing reduces U-values to approximately 3.0 $W/m^2 \cdot K$, while enhanced systems with gas fills and coatings can reach values near 1.0–1.4 $W/m^2 \cdot K$ [1], [11].

A key advancement that propelled IGUs into widespread adoption is the **low-emissivity (low-E) coating**, a thin metallic or metal oxide layer applied on the interior facing glass surface. This coating reflects longwave infrared radiation while allowing visible light transmission, thereby significantly reducing radiative heat transfer across the glazing [12], [13]. When applied in modern configurations especially in argon-filled units low-E coatings enable U-values as low as 1.0 $W/m^2 \cdot K$ or even below, with a concurrent reduction in SHGC [14], [15]. The cost premium of low-E glazing is relatively modest (~10–15%) yet offers substantial energy savings, cutting heat loss by 30–50% in typical applications [3].

Despite these developments, double and triple glazing solutions eventually reach diminishing returns. Even high-performance triple IGUs (with multiple low-E layers and inert gas fills) typically plateau around U ≈ 0.5 $W/m^2 \cdot K$ due to material and thickness

constraints [4], [16]. Additionally, such systems solely focus on reducing heat flow and do not recover any of the transmitted thermal energy.

An emerging alternative involves capturing this residual heat using **thermoelectric generators (TEGs).** Unlike passive glazing, TEG-integrated windows leverage the Seebeck effect to convert temperature gradients into electrical energy [17]. For instance, a Bi_2Te_3 based thermoelectric module can generate small but usable power outputs under moderate thermal gradients (e.g., ~100 μW at ΔT = 10 K per thermocouple) [18][19]. While thermoelectric integration remains a relatively recent innovation in building design, it offers a promising route to hybrid window systems that simultaneously reduce energy loss and produce power a gap largely unaddressed in conventional glazing [2], [20].

3. Emerging Passive Glazing Technologies.

Emerging passive glazing, technologies aim to reduce thermal losses and dynamically control solar gain without actively generating power. These innovations include Vacuum Insulated Glazing (VIG), Phase Change Material (PCM)-Integrated Glazing, and Chromogenic Glazing. Each of these approaches enhances energy efficiency through unique mechanisms, though they present implementation challenges.

3.1 Vacuum Insulated Glazing (VIG)

VIG represents a breakthrough in achieving ultra-low U-values by eliminating convective and conductive heat transfer across the inter pane gap. The unit typically consists of two glass panes separated by a ~0.2 mm vacuum gap supported by micro scale spacers and enclosed by hermetic edge seals [3], [21]. The vacuum layer drastically reduces heat flow, and internal low-E coatings help mitigate radiative transfer, allowing VIG systems to achieve U-values as low as 0.3–0.5 $W/m^2 \cdot K$ [22], [23].

VIG's slim profile makes it suitable for retrofitting historic windows and minimalist architectural designs. One study noted that a single-cavity VIG (total thickness ~21 mm) could match the insulation of a much thicker triple-pane IGU [24]. However, durability, edge sealing integrity, and the visibility of support pillars remain concerns [25], [26]. Advances in spacer materials and edge seal designs continue to address these limitations. Though cost remains high, energy efficiency mandates (e.g., R-10 rated windows) are driving VIG toward broader commercial use.

3.2. Phase Change Material (PCM) Integrated Glazing

PCM glazing enhances thermal regulation by embedding materials that absorb and release latent heat during phase transitions. Typically, these materials melt at ~22–30 °C and are placed as a laminated layer or within the glazing cavity. During daytime, the PCM absorbs solar heat (melting phase), reducing peak interior temperatures; at night, it solidifies, and releases stored heat, aiding thermal comfort [5], [27], [28].

PCM glazing systems have demonstrated effective U-values of ~0.48 $W/m^2 \cdot K$ and seasonal modulation of SHGC, from ~0.06–0.09 in summer to ~0.33–0.35 in winter [28]. Despite these benefits, optical transparency is a key limitation. Many PCMs become cloudy or opaque when transitioning and encapsulated or micro-dispersed PCM techniques are being developed to address this [29], [30]. Long-term material containment, added weight, and cost are also factors needing attention. Furthermore, PCM effectiveness is climate-dependent, requiring diurnal temperature variation for full energy cycling.

3.3 Electrochromic and Thermochromic Glazing

Chromogenic glazing systems adjust their transparency and solar heat gain dynamically. Electrochromic (EC) windows use voltage to change tint, while thermochromic (TC) systems respond to temperature shifts [4], [31], [32]. These technologies offer real-time adaptation to environmental conditions, reducing glare and managing solar load. For example, an EC window can shift from a clear state (VT = 0.60, SHGC = 0.50) to a tinted state (VT = 0.10, SHGC = 0.08), delivering substantial cooling load reductions [31]. MIT-developed TC films have demonstrated ~70% solar radiation blocking with 30% energy savings in test spaces [31].

Challenges include high costs, slow tint response times (especially for EC systems), wiring needs for EC, and non-uniformity in tinting. TC coatings offer wiring-free operation but have fixed activation temperatures and may suffer from uneven transition effects. Light transmittance in the clear state is also reduced compared to conventional glass (e.g., VT ~0.74 to 0.40 on tinting) [32]. Nevertheless, when combined with gas fills and low-E layers, chromogenic glazing can achieve U-values in the 1.5–2.5 $W/m^2 \cdot K$ range, making it a viable option for high performance buildings.

4. Energy Harvesting Windows

The advent of energy-harvesting windows marks a shift from purely passive glazing technologies toward systems that actively generate electricity. Two principal technologies in this domain are Photovoltaic (PV) Glazing and Thermoelectric Generator (TEG) Glazing. While PV glazing captures solar radiation, TEG glazing utilizes thermal gradients across window surfaces to produce electricity via the Seebeck effect. Each approach offers unique benefits and faces distinct limitations in power density, operational conditions, and integration feasibility.

4.1 Photovoltaic Glazing

Photovoltaic (PV) glazing integrates solar cells into window structures to convert incident solar radiation into electricity. Strategies include:

- Discrete cell layout, where crystalline silicon cells are spaced to allow partial transparency.
- Thin-film PV coatings, such as amorphous silicon or CdTe, applied as uniform semi-transparent layers [33].

These configurations result in tinted or patterned windows that balance light transmittance and power output. For example, a prototype by Photiou et al. achieved ~3–4% efficiency with ~50% visible transparency. Thin-film PV options typically yield 5–10% efficiency and visible transmittance (VT) below 10% [34].

Under direct sunlight (1000 W/m^2), traditional PV windows generate up to 50 W/m^2, depending on efficiency and active area. However, higher PV efficiency often entails lower transparency and greater visual obstruction [5], [34]. Their output is inherently intermittent, ceasing at night or under shade. They also double as solar heat blockers, reducing SHGC but introducing thermal buildup on the PV surface, which can reduce conversion efficiency [5].

While PV glazing supports net-zero energy goals by contributing electricity during daylight, it can significantly alter visual aesthetics and transparency. Current research focuses on developing transparent PV materials (e.g., perovskites, quantum dots) and aesthetic integration into architectural designs [33], [34].

4.2 Thermoelectric Glazing

Thermoelectric glazing (TEG windows) operates based on the Seebeck effect, where a voltage is generated when a temperature gradient (ΔT) exists across two dissimilar semiconductors typically p-type and n-type materials. In this context, thermoelectric generators (TEGs) are embedded in or adjacent to window assemblies to harness the temperature difference between the indoor and outdoor environments and convert it into electricity [6], [17]. Unlike photovoltaic systems, TEGs can function continuously, day or night, as long as ΔT is present.

Although TEGs exhibit relatively **low conversion efficiencies** (<5%), their advantage lies in continuous operation. For instance, Win *et al.* demonstrated a peak output of **610mW** from 12 TEG modules integrated along a window frame with a thermal gradient of approximately 10–15 K, corresponding to **~100 mW/m²** of window area [29]. Additional studies have shown that thermoelectric façades can achieve **outputs up to 2 W/m²** under favorable conditions [6], with more typical values ranging between **0.1–0.5 W/m²** [5], [9], [22].

Due to their form factor, thermoelectric modules are typically placed at the **perimeter or frame** of the window to minimize visual intrusion and maximize thermal gradients. Frame regions often experience higher ΔT due to their conductive nature and exposure to air leakage [29]. Some designs embed TEGs between glazing panes and incorporate **heat sinks or thermal interface materials** to optimize heat flow across the modules. Zinger *et al. demonstrated* that such configurations could self-power embedded sensors, enabling **autonomous smart windows** [20].

Beyond electricity production, TEGs inherently enhance the **thermal resistance** of window assemblies. By **converting heat flow into electrical energy**, they reduce the net conductive heat transfer through the glazing, thereby contributing to the **insulation performance** of the window [6], [7]. This dual role makes TEGs a functional addition to energy-efficient window systems.

Despite their promise, several **limitations** impede widespread adoption:

- Low power and voltage output under small ΔT conditions typical in buildings [29].
- Complexity in achieving **reliable thermal contacts, weather protection**, and **durability** for long-term use [7].
- Trade-offs between thermal insulation and heat flow: **maximizing ΔT requires allowing heat transfer**, which can reduce overall insulating performance.

Future research should aim to develop **advanced materials** with higher thermoelectric efficiency (i.e., higher figure of merit ZT), improve module **integration techniques**, and explore **hybrid configurations** that optimize both thermal performance and energy harvesting. Table I shows the comparison between photovoltaic glazing and thermoelectric glazing.

Table 1. Comparison between photovoltaic glazing and thermoelectric glazing.

Feature	Photovoltaic Glazing	Thermoelectric Glazing
Power Output	High (~10–50 W/m^2) under sun	Low (~0.1–2 W/m^2) continuously

Operating Condition	Sunlight only	Any ΔT (24/7 potential)
Transparency	Often reduced	Preserved (TEGs placed in frames)
Energy Form	Solar (radiative)	Thermal (conductive)
Output Stability	Intermittent	Continuous
Additional Benefits	Solar control/shading	Thermal insulation

Both systems offer complementary advantages. Hybrid PV+TEG designs are increasingly explored, where PV cells serve as **thermal absorbers** that enhance ΔT for adjacent TEGs, improving both electrical yield and thermal management [7], [5].

5. Research Gap in Energy Generating Glazing Technologies

5.1 Lack of Holistic Co-Optimization Frameworks

Most existing studies isolate the optimization of thermal insulation (e.g., low U-value and SHGC) from energy harvesting (e.g., TEG output) without considering their inherent trade-offs. Increasing thermal transmittance may enhance TEG power output but undermines insulation. As noted by Win et al., future designs must account for "complex tradeoffs between power output, system integration, and practical implementation" [9]. To address this, integrated multi-objective design tools are required that co-optimize window structure, frame materials, glazing types, and thermoelectric placement. Currently, such design frameworks remain underdeveloped.

5.2 Limited Experimental and Real-World Demonstrations

While PV and electrochromic prototypes are advancing toward commercialization, real-world implementations of thermoelectric (TE) glazing remain rare. Most TEG concepts have been validated only under short-term lab conditions, leaving significant uncertainty around durability under cyclic thermal stress, humidity exposure, and UV degradation over time [5], [9]. Long-term field studies and monitoring of prototype installations in varied climates are urgently needed to validate performance, maintenance requirements, and degradation profiles under realistic operating conditions.

5.3 Absence of Standardized Integration Methods

Unlike PV glazing, which benefits from emerging IEC standards and commercially available components, TEG integration lacks standardization. Each research team employs bespoke modules, mounting techniques, and performance metrics, impeding cross study comparisons. As identified in Gupta et al., scalable implementation demands "standardized methods for integrating TEGs into building components" [5]. For example, a plug-and-play "thermoelectric spacer" module could be standardized for window frames, along with consistent metrics such as watts per ΔT per square meter and a defined measurement protocol.

5.4 Scalability and Manufacturing Constraints

Advanced window technologies like vacuum glazing (VIG), aerogels, and TEG integrations face scalability challenges. Manufacturing large, uniformly evacuated glass units is difficult, and embedding multiple TEGs with electrical interconnections per window unit increases complexity and cost [28], [35]. Researchers highlight the need for film-based or printable thermoelectric materials to replace discrete ceramic modules, which are bulky and hard to scale [33]. Furthermore, climate adaptability remains underexplored: optimized designs for one zone may underperform in another. Systematic cross-climate simulations and multi-zone experimental validations are largely missing.

5.5 Lack of Lifecycle and Cost Benefit Analyses

Few studies evaluate the economic viability or carbon payback period of energy-generating windows. The embodied energy and material cost of advanced systems (especially tellurium-based TEGs or rare coatings) must be weighed against their operational benefits. Win *et al.* emphasize the need for life-cycle assessments and cost-reduction strategies to support policy and market adoption [5], [9]. Comprehensive studies evaluating return on investment and long-term energy savings across use cases are necessary to justify commercial deployment.

5.6 Interdisciplinary Modeling and Knowledge Gaps

TEG integrated glazing lies at the intersection of building science, material science, and electrical engineering fields that often operate in silos. Most building energy simulation tools (e.g., Energy Plus, TRNSYS) lack models for hybrid PV/TEG window systems, making it hard for designers to predict performance. Conversely, many thermoelectric material studies neglect practical architectural constraints like aesthetics, light transmission, or façade load integration. To bridge this divide, interdisciplinary frameworks and modular simulation plug-ins for PV/TE windows are needed. Table 2 below describes the summary of research gaps in this review.

Table 2: The summery of research gaps.

Gap Area	Description
Co-Optimization	Lack of integrated tools balancing thermal insulation and power generation
Field Validation	Scarcity of long-term, real-world pilot studies

Standardization	No industry protocols or performance benchmarks for TEG-glazing integration
Scalability	Manufacturing and design complexity in large-area or multi-zone applications
Lifecycle Costing	Incomplete data on cost-effectiveness and energy/carbon payback
Interdisciplinary Integration	Poor integration between architectural design and thermoelectric materials research

6 FUTURE RESEARCH DIRECTIONS

6.1 Advanced Thermoelectric Materials with Higher ZT

Enhancing the performance of thermoelectric glazing (TEG) requires breakthroughs in thermoelectric materials. Current Bi_2Te_3-based modules exhibit a figure of merit ZT≈1 at room temperature. For meaningful improvements in conversion efficiency, materials with ZT=2 to 4 or higher are needed [7]. Promising candidates under investigation include skutterudites, half Heusler's, conductive polymers, and nanostructured composites [6]. For building integration, these materials must perform well within 10–40 °C the typical window operating range. Emerging flexible and transparent thermoelectric films, such as CNT- or polymer-based devices, could allow lamination along glass edges, though their efficiency remains lower than bulk thermoelectric. Additionally, modules tuned for low ΔT (5–10 K) are required, potentially with dense thermocouple arrays to boost voltage. Material innovation is therefore foundational for improving TEG window efficiency [7].

6.2 Thermal Enhancement Techniques

Thermal augmentation strategies can increase the effective ΔT across TEGs. Heat pipes or high-conductivity fins embedded in window frames can passively deliver or dissipate heat to enhance power generation. Kang et al. showed that micro heat pipes improved output in a PV-TEG wall by improving heat distribution [5]. Similarly, loop heat pipes or thermal concentrators such as selective solar absorbing coatings can locally raise ΔT by targeting thermal flux toward TEGs [6]. Integrating phase-change materials (PCMs) with TEGs adds thermal storage, allowing continuous or delayed heat flow across the device. Although Ko and Jeong reported modest gains (~1% annually) with a PCM-TEG-PV system [5], alternative PCM configurations or melting points may yield greater benefits.

6.3 Hybrid Integration of Multiple Technologies

Multifunctional "smart" windows combining PV, TEG, PCM, and chromogenic components can leverage synergies among technologies. For instance, semi-transparent PV handles daytime solar electricity generation, while TEGs scavenge low-grade waste heat or nighttime gradients [5], [6]. TEGs can also enhance PV performance by cooling cells [5]. Integrating PCMs to stabilize ΔT, or electrochromic glazing to modulate IR absorption, could further improve output and control. Tyagi emphasized the potential of hybrid multifunctional glazing systems that manage light, heat, and electricity simultaneously [15]. Integrated transparent conductive oxide (TCO) films may also offer

active temperature modulation via resistive heating or cooling when surplus energy is available.

6.4 Long Term Durability and Performance Studies

Robustness under real-world conditions is crucial. TEG modules in windows will face thermal cycling (e.g., 0–40 °C), humidity, and UV exposure. Studies must evaluate thermal fatigue, encapsulation effectiveness, and material compatibility with glazing seals. Long-term field testing across diverse climates (e.g., hot-humid vs. cold-dry) will validate performance over time. Dust, condensation, and degradation of coatings (low-E, PV, TEG films) should also be investigated. Win et al. stress the need for durability-focused research, as material degradation can significantly affect long-term TEG performance [5].

6.5 Development of Standards and Simulation Tools

The absence of standardized metrics hinders adoption. Developing an IEEE/ASHRAE guideline for hybrid photovoltaic-thermoelectric fenestration could define performance benchmarks (e.g., effective U-factor with power output, “net energy window rating”). Integration into building simulation tools (Energy Plus, TRNSYS) would allow architects to evaluate trade-offs. Simplified circuit models of TEG windows could aid parametric simulations. Smart building integration frameworks are also needed; as Win et al. highlight, dynamic control strategies (e.g., temporarily disabling TEGs for thermal optimization) could optimize building energy management [5].

6.6 Interdisciplinary Demonstration Projects

Pilot projects involving architects, materials scientists, and engineers are essential to demonstrate viability. A model project could involve a net-zero building equipped with hybrid windows e.g., triple-glazed, low-E, TEG and PV integrated units. Such testbeds can reveal practical challenges (e.g., thermal bridging, wiring logistics) and provide empirical data to refine designs. Collaboration among universities, national labs, and manufacturers is recommended to scale these prototypes and explore economic feasibility.

7 Conclusion

Windows, once the weakest link in the building envelope, are rapidly transforming into multifunctional elements central to energy-efficient architecture. While conventional advances in glazing such as low-emissivity coatings, vacuum insulation, and dynamic shading have significantly improved thermal performance, a new paradigm is emerging energy generating glazing systems that not only reduce energy loss but also actively produce power.

This review has shown that photovoltaic (PV) glazing enables electricity generation from sunlight, particularly beneficial for high rise façades, while thermoelectric generator (TEG) integration offers round the clock energy harvesting from temperature differentials. Together, these technologies can be merged into hybrid smart windows capable of insulation, solar control, and continuous power generation. Such windows hold promises for powering embedded sensors, enabling autonomous climate responsive control, and contributing meaningfully to net-zero energy goals.

However, several challenges remain. Thermoelectric efficiency must improve through

advances in materials (e.g., high-ZT compounds), and cost effective, scalable integration methods must be developed. Crucially, interdisciplinary collaboration between materials science, thermal engineering, and architectural design is needed to ensure performance, aesthetics, and economic viability.

Encouragingly, ongoing progress in nanomaterials, IoT integration, and building automation systems indicates strong momentum. With coordinated research and policy support, energy generating windows can evolve from experimental concepts into standard building elements. In doing so, they may redefine the role of windows from passive daylight portals to active, intelligent components of sustainable, resilient buildings.

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Intelligent Beam Pattern Modulation for Automotive Headlights Using Adaptive LED Matrix Based Headlights

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Abstract—Night-time driving presents significant challenges, particularly due to the glare caused by oncoming vehicles' headlights, which can severely hinder visibility. This research proposes an intelligent adaptive headlight control system which utilizes intelligent beam pattern modulation, using LED matrix technology to enhance both safety and comfort during night driving. By dynamically adjusting individual LEDs in real time according to detected vehicles, the system aims to optimize road illumination while minimizing glare for other road users. Unlike traditional static headlights, this solution integrates stereo vision inputs and smart controllers to intelligently modify beam patterns based on situational context. The system is built with a strong focus on real-world applicability and has been prototyped and tested in simulated driving environments to evaluate its performance. The ultimate objective is to deliver a responsive lighting system that maintains optimal visibility for the driver while preventing discomfort for others on the road.

Keywords—Adaptive Headlights, Automated Headlights, Driver Safety, Matrix Headlights, Night-time Driving

I. INTRODUCTION

Night driving remains a critical challenge due to diminished visibility and glare from opposing headlights, which can significantly impair a driver's vision and increase accident risk. According to statistics from the World Health Organization, individuals aged 15 to 64, who predominantly drive during nighttime account for over 70% of global road traffic accidents. This highlights the urgent need for advancements in automotive lighting technology. As a response, researchers and manufacturers have recognized the potential of intelligent lighting systems capable of automatically adjusting beam patterns to relieve drivers from manual control and prevent improper usage [1].

Adaptive lighting technologies, such as Adaptive Driving Beam (ADB) systems, have emerged to address this need. These systems utilize arrays of independently controllable LEDs that dynamically illuminate the road while selectively dimming or turning off specific regions to avoid causing glare to other drivers [2]. Modern implementations like Mercedes-Benz's MultiBeam LED headlights which was introduced in 2016 demonstrate the capabilities of high-resolution LED matrix headlights to autonomously adapt lighting conditions [3]. However, such systems remain predominantly available in luxury vehicle segments due to their high cost.

To bridge this gap, the system proposed in this research adopts cost-effective components and integrates real-time data to intelligently control each LED within the matrix. This enables precise beam shaping that maintains visibility for the driver while reducing glare for oncoming traffic. Prior studies suggest that such sensor driven adaptive lighting can be implemented affordably, making the technology accessible for mid-range vehicles [4]. The proposed design further develops this idea by incorporating

computer vision techniques for oncoming vehicle detection, followed by algorithmic beam modulation based on spatial positioning. This research seeks to deliver a functional, low-cost adaptive headlight system capable of mitigating glare through precise beam modulation, providing high-end safety features to a broader market.

2. Related Studies

Recent research in adaptive headlighting has largely emphasized sensor-based systems due to their simplicity and dependability. For instance, automatic high beam dimming systems use LDRs and relays to toggle between low and high beams based on the detection of headlights or taillights from nearby vehicles [5]. Snehal G. Magar introduced an Automatic Adaptive Front Lighting System that enhances visibility during night driving by adjusting headlamp angles based on road curvature. This system utilizes cameras and ultrasonic sensors to align the headlight direction dynamically, thereby minimizing glare for oncoming traffic [6]. Arpita Banik et al. presented a method using stepper motors to adjust headlamp orientation according to the steering angle, which is detected using a potentiometer. The system also includes an LDR-based dimmer that automatically reduces or disables the high beam depending on ambient lighting conditions [7]. Based on the use of LED matrices, Ashik et al. proposed a system where a steering-column-mounted potentiometer measures steering input and feeds this data to an Arduino controller. The Arduino controller then turns on or off several LEDs toward the bend, on each side of the car for maximum visibility around the corner [8]. Some approaches enhance perception by combining camera data with radar or LiDAR through Kalman filter-based fusion, improving object detection accuracy. Others incorporate stereo or time-of-flight cameras and IMUs for depth estimation [9]. Advanced designs even integrate radar or LiDAR directly into the headlamp unit, sharing the same optical axis with LEDs [10]. López et al. designed a specialized automotive image sensors which can mitigate glare and enhance night vision [11]. Combining RGB and near-infrared imagery further improves detection reliability in low-visibility conditions [12]. Archana Burujwale et al. proposed a computer vision-based matrix LED headlight system using WS2812 LED matrices and computer vision algorithms [13]. The Smart Vehicle Headlight Auto Switching and Intensity Control system uses an Arduino to coordinate GSM and GPS for emergency warnings, as well as LDR-based light adjustment, ultrasonic obstacle detection, and MEMS-based accident sensing [14]. With real-time hardware validation appropriate for mid-range vehicles, Gnanasekaran et al. proposed a low-cost adaptive headlight system that uses an LDR and a microcontroller to automatically tilt headlamps upward or downward based on detected light levels, reducing glare and enhancing night driving safety [15].

Fuzzy logic controllers have been used to translate inputs such as ambient light, steering angle, and proximity to oncoming vehicles into continuous brightness adjustments, offering robustness in uncertain conditions [9]. Q-learning has also shown promise, allowing the system to adapt brightness in response to environmental changes and learn optimal lighting strategies over time, enhancing both safety and energy efficiency [16]. CNNs trained on nighttime datasets enable accurate detection of distant vehicles and help define specific beam dimming zones. Somasiri et al. demonstrated a deep learning-based object detection framework specifically designed for adaptive beam control in vehicles [17]. Additionally, predictive control using multi-input multi-output (MIMO) models has been employed to achieve stable and accurate beam modulation, with convergence times as low as 0.7 seconds [18].

While current adaptive lighting systems offer advanced functionality, they are often costly and complex, limiting their use to high-end vehicles. This research proposes a simplified, low-cost solution using stereo vision and rule-based control to enable precise, real-time glare mitigation making adaptive headlights more accessible for mid-range vehicles. The key innovations of this work include:

- A novel LED masking algorithm.
- Pixel wise control of an LED matrix.
- Real-time 3D vehicle localization using stereo vision, eliminating the need for sensor fusion.

3. METHODOLOGY

To create a cost-effective adaptive headlight system capable of real-time glare reduction, the methodology combined stereo vision, computer vision algorithms, and programmable LED hardware. Emphasizing practicality and modularity, affordable components such as addressable LED matrices and a stereo camera were used to detect vehicle positions and adjust lighting at the segment level. An iterative prototyping approach ensured system functionality in both lab and real-world conditions. The following sections detail each development stage.

3.1 Hardware Selection

The prototype system mainly consisted of:

- An 8×32 WS2812b RGB LED matrix
- A stereo vision camera
- An Arduino Mega microcontroller

These components were selected to balance performance and affordability, ensuring scalability for wider automotive adoption.

3.2 System Architecture

The system was built using an 8×32 WS2812b LED matrix, a GxiVision stereo vision camera, and a microcontroller. The stereo vision camera was calibrated using standard stereo calibration procedures. The main processing tasks, which are vehicle localization and control logic, were implemented in Visual Studio Code (VSCode).

A Python-based computer vision pipeline was developed within VSCode. Video input from the stereo camera was processed using OpenCV, employing filtering techniques to generate disparity

maps and calculate depth information. YOLO was integrated for object detection, enabling the identification of oncoming vehicles within each video frame. Using depth information, the detected vehicle was localized, and depth data was fed into the control algorithm.

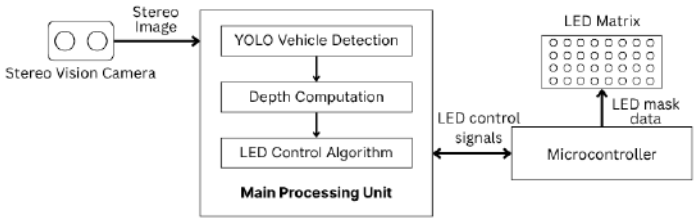

Fig. 11. System Architecture

The WS2812b LED matrix was driven by a microcontroller, which was preprogrammed to receive LED masking commands from the VSCode platform via serial communication protocol. Based on these commands, the microcontroller dynamically adjusted the LED output patterns. The overall system architecture is illustrated in Fig. 1.

3.3 LED Matrix Control Algorithm

The algorithm is fundamentally based on the light intensity principle, which states that light intensity decreases proportionally with the square of the distance from the source. Hence, objects farther from the headlight receive lower light intensity.

Utilizing live stereo image feeds from the stereo vision camera, the YOLO object detection model was employed to identify vehicles within the scene and then a bounding box was drawn around them. A center point was then determined within the bounding box, and the distance from the camera's origin point (0,0,0) to this center was computed. Fig. 2. illustrates the detected vehicles with bounding boxes around them.

Depth estimation was performed using the disparity map and the triangulation formula derived from the principles of stereo vision geometry. Disparity refers to the difference in the position of the same point in two stereo images, one captured by the left camera and the other by the right camera in a stereo vision system. Disparity is calculated using Equation (1):

*Fig. **2**. Identified vehicles with distances*

$$Disparity = x_{left} - x_{right} \qquad (1)$$

Where:

- x_{left} = Horizontal coordinate (in pixels) of the left camera image
- x_{right} = Horizontal coordinate (in pixels) of the right camera image

Once the disparity is obtained, the corresponding depth for each point in the scene can be calculated using the triangulation formula derived from stereo vision principles. This relationship is expressed in Equation (2):

$$Depth = \frac{f \cdot B}{d} \qquad (2)$$

Where:

- f = Focal length of the camera (pixels)
- B = Baseline distance / distance between the two camera centers (meters)
- d = Disparity value (pixels)

This formula allows accurate depth estimation for each detected object using the known stereo calibration parameters.

The 3D coordinates of each individual LED in the matrix, relative to the stereo vision camera's origin point (0,0,0), were pre-recorded. Using these coordinates, along with the real-time coordinates of the detected vehicle, the Euclidean distance between each LED and the vehicle was computed. The Euclidean distance represents the shortest straight-line path between two points in 3D space and is derived from the Pythagorean theorem. The formula for calculating the Euclidean distance between two points in three-dimensional space is given by Equation (3):

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \qquad (3)$$

Where:

- d = Euclidean distance between two points
- (x_1,y_1,z_1) = coordinates of the first point (e.g., LED position)
- (x_2,y_2,z_2) = coordinates of the second point (e.g., vehicle position)

Once the Euclidean distances were determined, the light intensity at the vehicle's location from each individual LED was calculated using the light intensity equation (4). In this context, luminosity represents the power of the light source, measured in lumens. The relationship is described by the following Equation (4):

$$Intensity = \frac{Luminosity}{4\pi d^2} \qquad (4)$$

Here, 'd' denotes the Euclidean distance between a given LED and the vehicle's position. To determine the total illuminance at that point, the contributions from all LEDs were summed. These individual intensities were sorted in descending to track which LEDs contributed most to the total brightness at the vehicle's location. This enabled the algorithm to iteratively disable the highest-contributing LEDs, one by one, until the calculated intensity at the critical point dropped below a predefined comfort threshold. This approach effectively reduced glare for oncoming or leading vehicles while preserving sufficient illumination for the driver.

3.4 Prototype Testing

A functional prototype was developed to evaluate the system's performance. As an initial test, vehicle coordinates were manually provided to the algorithm to generate the LED

masking pattern. Once the masking logic was verified, the system was transitioned to use real-time vehicle coordinates obtained from the stereo vision camera for testing.

Fig. 3. displays the dynamic masking patterns created by the algorithm in response to detected vehicles at different distances, which are transmitted to the LED matrix for execution.

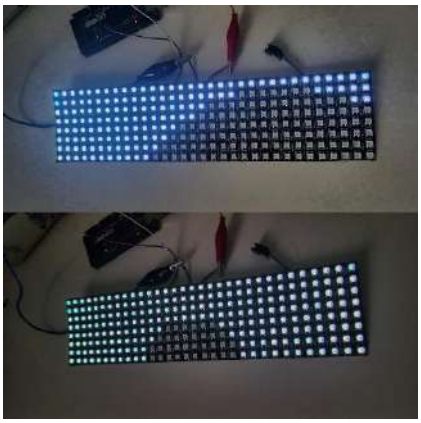

*Fig.**3**. LED matrix with dynamic masking patterns*

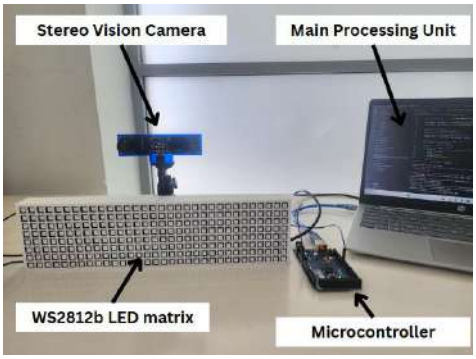

Fig. 412. Experimental setup

This iterative, practical development approach ensured the system was not only effective under real-world conditions but also modular and adaptable for future improvements or integration into various vehicle platforms.

Fig. 4. presents the physical prototype setup, which includes the mounted 8×32 WS2812b LED matrix encased in a 3D-printed housing for structural support and portability. The stereo vision camera is positioned at a fixed height and orientation relative to the LED array to simulate its placement in a vehicle's front fascia. Wiring is routed to an Arduino Mega microcontroller, which receives LED control commands via serial communication from a host computer running the vision and detection pipeline. This compact arrangement allows for controlled testing of beam modulation and LED masking in simulated environments, validating the system's basic functionality prior to real-world deployment.

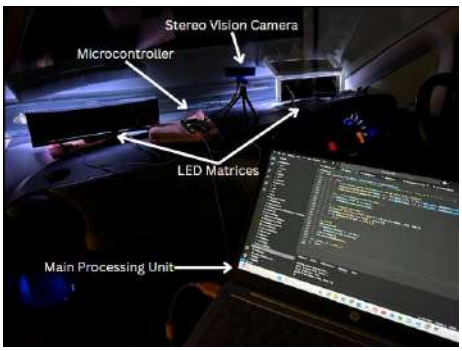

Fig. 513. Experimental setup mounted in vehicle

Fig. 6. Dynamic lighting patterns

Fig. 5 shows the testing vehicle along with LED masking patterns according to the detected front vehicle and fig. 6 shows the testing vehicle along with LED masking patterns according to the detected front vehicle.

4. RESULTS AND DISCUSSION

Present This research project demonstrates effective performance in detecting vehicles and generating LED masking patterns that reduce glare for both oncoming and preceding traffic. The implemented LED matrix offers precise beam control with segment-level modulation, enabling targeted illumination. The system achieves a response time of less than 100 milliseconds from object detection to LED adjustment, ensuring seamless real-time operation.

A comparative analysis of light intensities of the proposed adaptive headlight system is presented below to further validate its effectiveness.

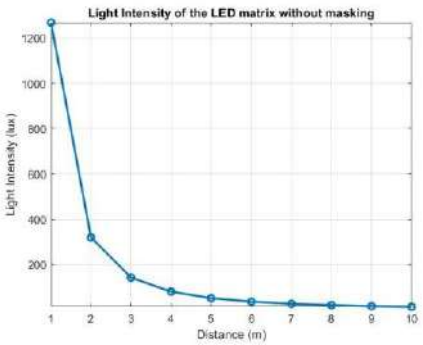

Fig. 7. Light distribution curve of WS2812b LED matrix without masking

As shown in Fig. 7. the light intensity of the LED matrix diminishes as the distance increases. There is no difference between a traditional headlamp and an unmasked LED matrix. They both do not account for traffic and blindly illuminate the surroundings ahead.

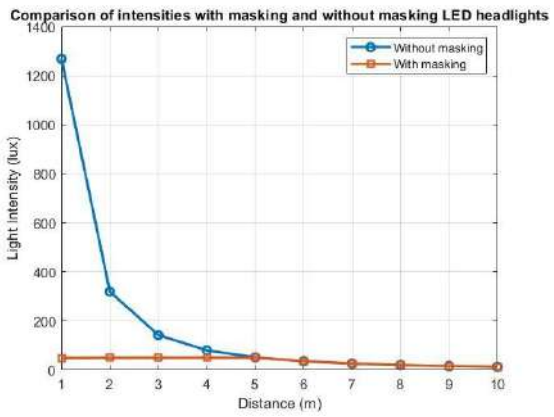

Fig. 8. Comparison of the LED matrix with and without masking

Fig. 8. illustrates the light distribution curves of the LED matrix with masking and without masking. Light distribution curve of the without mask is plotted in blue color while the with masking light distribution curve is plotted in blue. With masking curve has fixed values of 50 lux over the distances indicating that the algorithm effectively maintains the light intensity at a constant threshold level using dynamic masking patterns. However, when the initial lux is already below the threshold level, the algorithm retains the original intensity, keeping all LEDs active to ensure adequate illumination.

These results underscore the effectiveness of the adaptive headlight design in mitigating glare. Unlike the unmasked LED matrix, which displays significant fluctuations in lux levels that often surpass comfort thresholds, the masked configuration delivers a stable and controlled light output across varying distances. This confirms the system's ability to regulate beam intensity in real time through pixel level masking.

By keeping illumination below discomfort thresholds at key points, the system enhances driving safety while remaining scalable and cost-efficient. These findings validate the practicality and impact of employing stereo vision with segment-level LED control for intelligent, glare-reducing automotive lighting.

Despite the successful development and validation of the proposed adaptive LED matrix headlight system, some latency in image processing and LED updates was observed. Furthermore, the system's exclusive reliance on stereo vision poses challenges in low-visibility environments. Also, the system was not tested in adverse weather conditions such as heavy rain, fog, or snow, which could significantly affect the stereo vision accuracy and overall system performance.

5. CONCLUSION

This paper presents the development of an adaptive headlight system that leverages beam pattern modulation with a cost-effective LED matrix and rule-based control strategies to enhance night-time driving safety and reduce glare for oncoming traffic. In contrast to conventional fixed-beam headlights and premium adaptive lighting systems found in luxury vehicles, the proposed solution offers a modular, affordable, and scalable alternative tailored for mid-range vehicles. Experimental results show notable improvements over traditional lighting systems, particularly in terms of adaptability, responsiveness, and overall glare mitigation. The design also exhibits strong fault tolerance and flexibility, supporting integration into diverse automotive platforms. To further enhance performance, future iterations of the system may incorporate machine learning models to enable predictive beam adjustment based on traffic patterns, road context, and historical data. Additionally, integrating environmental sensing, such as rain or fog detection and dynamic driver assistance features can further improve adaptability and safety under diverse conditions. These improvements could evolve the current rule-based approach into a fully autonomous and context-aware headlight control system.

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TECHNICAL SESSION 5

CIVIL ENGINEERING & ARCHITECTURE

An Evaluation of The Impact of Interior Lighting on User Task Performance in LEED Certified Buildings

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Abstract—This study examines the influence of interior lighting on user task performance within office environments of LEED-certified and non-LEED-certified buildings. The primary objective is to evaluate how different lighting parameters such as illuminance levels, natural daylight availability, glare control, and user control features affect employees' ability to perform visual and cognitive tasks, including reading, writing, and computer-based work. The research adopts a comparative case study approach involving four office buildings: two LEED-certified and two non-LEED-certified. Data collection methods included quantitative illuminance measurements and qualitative user surveys to assess both objective lighting performance and subjective user satisfaction. The results reveal that LEED-certified buildings demonstrate higher visual comfort, more consistent lighting quality, and greater energy efficiency due to the integration of natural lighting and adaptive control systems. In contrast, non-LEED buildings often exhibit uneven lighting distribution and limited user control, which may adversely affect task performance and workplace well-being. The findings underscore the significance of effective lighting design in promoting occupant productivity and comfort, while reaffirming the contribution of sustainable lighting practices to the overall performance of green-certified office environments.

Keywords— Interior lighting, user task performances, LEED certification

1. INTRODUCTION

Interior lighting plays a vital role in influencing how individuals perform their daily tasks within office environments. Proper lighting enhances focus, reduces eye strain, and improves overall comfort and productivity. In recent years, many office buildings have adopted green certification systems such as LEED (Leadership in Energy and Environmental Design) to promote energy efficiency and create healthier indoor environments. LEED-certified buildings are designed with advanced lighting strategies that incorporate natural light, smart control systems, and energy-efficient lighting solutions. As LEED certification has become a globally recognized framework for promoting sustainable building practices, it offers valuable insights into how interior design decisions particularly lighting affect users' well-being and performance. Therefore, this study aims to evaluate how interior lighting influences user task performance in both LEED-certified and non-LEED-certified office buildings. By comparing these two types of work environments, the research seeks to determine whether green-certified buildings truly enhance user comfort and productivity.

The central research question guiding this study is how interior lighting affects user task performance in LEED-certified office areas compared to non-LEED-certified office areas. Accordingly, the study aims to evaluate how interior lighting contributes to user task performance in LEED-certified office buildings. The specific objectives are to identify the quality of interior lighting in LEED and non-LEED office buildings, to assess the impact of interior lighting on user task performance in both building types, and to compare user perceptions and experiences related to lighting and task efficiency between LEED and non-LEED office environments.

2. LITERATURE REVIEW

Lighting plays a crucial role in office design, significantly influencing user comfort, visual performance, and productivity. The appropriate selection and implementation of lighting criteria depend largely on the type of office, as different spatial configurations such as open-plan, private, and hybrid offices demand varying illumination strategies to ensure both uniform brightness and task-specific lighting efficiency [1]. Effective glare control is also vital, as unmanaged brightness from direct light sources or reflective surfaces can cause visual discomfort and impair visibility, particularly when using computers [2], [3]. General lighting provides the overall ambient illumination necessary for daily activities and is one of the primary contributors to building energy consumption, making energy-efficient solutions such as LEDs and automated controls essential [4]. Complementing general lighting, task lighting offers focused illumination for activities like reading, writing, and computer work, directly enhancing user performance and comfort [5]. Office environments typically utilize a combination of natural, general, and task lighting sources to balance comfort, energy efficiency, and visual quality [6]. While artificial lighting offers controllability and uniformity, natural daylight contributes to occupant well-being by supporting circadian rhythms and improving mood, underscoring the need for designs that harmonize both types of light [6]. The integration of lighting design principles within green building frameworks, particularly the Leadership in Energy and Environmental Design (LEED) certification system, further emphasizes the importance of sustainable and user-centered illumination. LEED promotes healthy, efficient, and environmentally responsible buildings by setting standards for lighting performance through credits related to lighting control and lighting quality. These include providing individual or multi-zone controls, using high-CRI (Color Rendering Index) light sources, and maintaining luminance levels below 2500 cd/m^2 to reduce glare and enhance visual comfort [7], [8]. Collectively, the reviewed literature underscores that well-designed lighting systems integrating natural and artificial light, glare management, and user control are essential for improving task performance, comfort, and sustainability in both conventional and green-certified office environments.

3. METHODOLOGY

This study adopts a qualitative research methodology to investigate the impact of interior lighting on user task performance in LEED-certified office buildings. The approach focuses on understanding how lighting design strategies implemented under LEED standards contribute to improving work performance and user comfort. Qualitative methods were selected to enable an in-depth exploration of user experiences, perceptions, and satisfaction related to lighting conditions within their work environments. The research process involves the selection of case studies representing both LEED-certified and non-LEED-certified office buildings, allowing for comparative

analysis of lighting performance and its effects on task efficiency. Data collection methods include direct observations, illuminance measurements, and user surveys to gather insights into both the physical and perceptual aspects of lighting quality. The findings from these multiple sources are analyzed thematically to identify patterns, relationships, and variations in lighting impacts across different building types. This methodological framework enables a comprehensive understanding of how sustainable lighting practices influence user task performance, contributing to evidence-based design strategies in contemporary office environments.

4. RESULTS AND DISCUSSION

The analysis compares lighting conditions in LEED-certified and non-LEED-certified office buildings to assess their impact on user task performance.

In the **HNB Bank Nittambuwa** branch, large glass walls allow ample daylight, but uneven lighting levels (108–627 lux) and glare from direct sunlight create visual discomfort. Although blinds are used, the absence of personal lighting controls limits user adaptability. Similarly, the **DIMO 800 Mercedes-Benz** office benefits from natural daylight but experiences severe glare and inconsistent illumination ranging from 49 to 1200 lux. The lack of automatic blinds or glare-reduction systems further reduces visual comfort and task efficiency.

In contrast, the **Commercial Bank Gampaha** office relies mainly on artificial lighting due to limited daylight access. While this minimizes glare from sunlight, it results in uniform but less dynamic lighting without user control or glare-reduction features. The **Hayleys Fentons** office in Maradana also depends entirely on electric lighting, maintaining suitable brightness levels (352–804 lux) but lacking the health and psychological benefits of natural daylight.

Overall, LEED-certified buildings demonstrate a stronger emphasis on natural lighting, supporting sustainability goals but facing challenges with glare and uneven illumination. Non-LEED-certified offices provide more consistent artificial lighting yet lack environmental quality and user control features. The findings highlight the need for balanced lighting strategies that integrate natural and artificial light while ensuring comfort, efficiency, and adaptability for office users.

The questionnaire survey results further support the findings from the case studies, revealing notable differences between LEED-certified and non-LEED-certified buildings in terms of lighting quality and its impact on user performance. The data illustrated in Figure 1 demonstrates the consistency of lighting across workstations throughout the day. A majority of respondents from LEED-certified offices reported that their workspaces maintained stable and uniform lighting levels during working hours. This consistency indicates that LEED lighting systems, which integrate both natural and artificial sources with better control mechanisms, effectively support continuous task performance without causing visual strain or interruptions. In contrast, non-LEED office

users experienced more fluctuations in light levels, often requiring adjustments such as repositioning or using blinds, which could disrupt workflow and concentration.

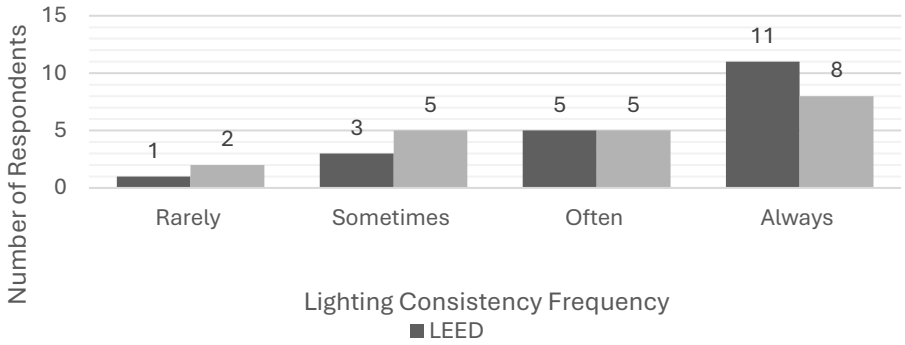

Fig.1. Consistency of Lighting at Workstations in LEED and Non-LEED-Certified Offices

Figure 2 highlights the relationship between poor lighting conditions and reduced work accuracy or speed. The responses show that both LEED and non-LEED users reported a decline in task performance under inadequate lighting levels, reinforcing that insufficient or uneven illumination negatively affects concentration, visual comfort, and efficiency. However, the overall responses indicate that LEED-certified office users face such issues less frequently due to improved lighting design and better integration of control features.

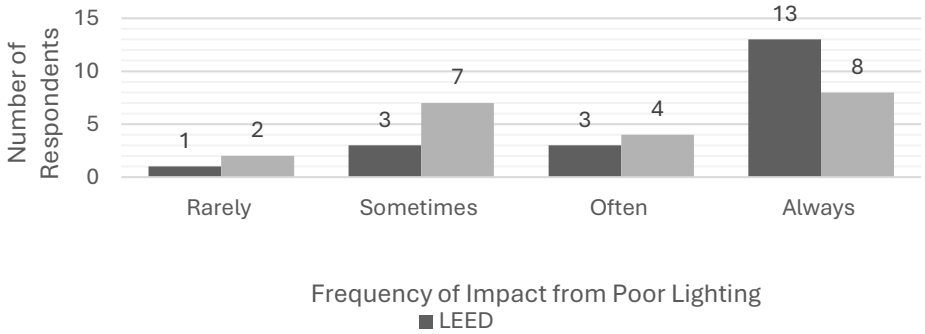

Fig.2. Comparison of the Impact of Poor Lighting on Work Accuracy and Speed between LEED-Certified and Non-Certified Users

Overall, the questionnaire findings confirm that effective lighting design significantly enhances productivity and user satisfaction. LEED-certified buildings demonstrated higher lighting consistency, better visual comfort, and greater user awareness of their lighting environment, enabling employees to perform tasks more efficiently and comfortably. Conversely, non-LEED offices showed a need for improved lighting management to ensure both comfort and performance. These results underscore the positive contribution of sustainable lighting design in promoting occupant well-being and supporting effective work environments.

5. CONCLUSION

This study investigated the impact of interior lighting on user task performance by comparing LEED-certified and non-LEED-certified office buildings in the Western Province of Sri Lanka. The findings reveal a significant difference in lighting quality, consistency, and user satisfaction between the two categories. LEED-certified buildings demonstrated the effective integration of sustainable lighting strategies such as the use of energy-efficient LED fixtures, optimized natural daylighting, and adaptive lighting control that enhance both visual comfort and energy performance. These features contribute to a well-balanced luminous environment that supports concentration, reduces visual fatigue, and promotes overall occupant well-being.

In contrast, non-LEED-certified buildings were found to lack advanced lighting technologies and daylight optimization, leading to irregular illumination levels and limited user control over lighting conditions. Such shortcomings may negatively affect occupants' task accuracy, visual comfort, and long-term productivity. The results of the user survey further emphasized that lighting consistency and individual control are critical determinants of task efficiency, underscoring the psychological and physiological importance of well-designed lighting systems in workplace environments.

Overall, the study concludes that LEED-certified buildings provide superior lighting environments that not only improve user comfort and productivity but also align with global sustainability goals. The research highlights the necessity of incorporating sustainable lighting principles, such as proper daylight integration, glare control, and user adaptability into future office designs, regardless of certification status. By prioritizing lighting quality as a key design criterion, architects and interior designers can create healthier, more efficient, and environmentally responsible workspaces that foster human performance and satisfaction.

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AN EXPERIMENTAL STUDY ON THE IMPACT OF INTERIOR LIGHTING CONDITIONS ON PLANT GROWTH

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Abstract—This study examines the influence of artificial light intensity on the growth performance of selected indoor plant species within residential apartment environments. Three common houseplants Aglaonema modestum, Philodendron hederaceum, and Alocasia amazonica were exposed to three varying intensities of LED light (low: 20W, medium: 36W, and high: 50W) over a 14-day period under continuous 24-hour illumination. The experiment was conducted in a controlled setting replicating typical apartment conditions, with regular monitoring of leaf health, growth rate, new leaf emergence, and visible stress indicators. Results indicated that Aglaonema and Philodendron exhibited optimal growth under low and medium light intensities, whereas Alocasia demonstrated stress symptoms under medium and high light levels. Additionally, Aglaonema showed evidence of scale insect infestation under high-intensity lighting. The findings highlight the potential of artificial lighting to support vegetative growth in multi-storey residential interiors while emphasizing the importance of appropriate light intensity to prevent plant stress. The study further underscores the biophilic benefits of integrating healthy indoor vegetation into apartment living environments.

Keywords— Biophilic design, Artificial lighting, Apartment interiors, indoor plant, Light intensity

1. INTRODUCTION

The increasingly urbanized nature of modern living environments has gradually diminished the natural connection between humans and the natural world, emphasizing the need for biophilic design in contemporary residential spaces. Among the various strategies that embody biophilic principles, the integration of indoor plants within apartment interiors has become increasingly popular due to their significant psychological and aesthetic benefits. While artificial lighting provides a practical substitute for natural sunlight, limited research has been conducted on its long-term effects on plant health and growth within enclosed residential environments. This study explores the growth responses of common indoor plant species under different intensities of artificial lighting, aiming to provide valuable insights for apartment residents and interior designers seeking to optimize plant vitality and enhance ecological and psychological well-being.

Biophilic design underscores humanity's inherent affinity with nature, making it particularly relevant within compact urban apartments. Incorporating vegetation into interior spaces not only improves air quality and microclimatic comfort but also

contributes to enhanced mental health and emotional satisfaction [1]. Indoor plant species such as Alocasia amazonica, Aglaonema modestum, and Philodendron hederaceum exemplify how vegetation can enrich apartment interiors both visually and functionally, supporting the creation of restorative and life-affirming environments [2], [3].

Lighting plays a fundamental role in sustaining plant health, particularly in apartment contexts where access to natural sunlight is restricted. To promote the growth of indoor vegetation in such low-light environments, biophilic interior design increasingly incorporates artificial lighting systems, with light-emitting diodes (LEDs) being particularly favored for their energy efficiency, controllable light spectrum, and minimal heat emission [4].

Both light intensity and spectral quality are crucial determinants of plant growth, as photosynthetic activity relies on an optimal balance of blue and red wavelengths. LED technology allows precise control over these parameters, making it an ideal solution for compact residential settings. Proper light management not only ensures healthy plant development but also reinforces the objectives of biophilic design by sustaining greenery in interior environments [5], [6].

2. RESEARCH METHODOLOGY

This study investigates the influence of artificial light intensity on the growth performance and physiological response of indoor plants under simulated apartment conditions. The methodology integrates both quantitative and qualitative approaches to provide a comprehensive understanding of plant adaptation to artificial lighting. The experiment was conducted over a period of 14 days, under controlled interior environmental conditions, to evaluate variations in growth rate, leaf development, and visible stress symptoms across different light intensity levels.

Experimental Design and Process- A mixed-method approach was employed, combining measurable quantitative growth data with qualitative visual assessments of plant health. The experiment was designed to simulate continuous exposure to artificial lighting, representing extreme indoor apartment conditions where natural daylight is limited. To ensure consistency, all plants were subjected to constant illumination for 24 hours per day throughout the 14-day testing period. Observations were recorded twice daily to monitor progressive growth behavior, leaf formation, and any signs of stress or infestation.

Plant Selection and Preparation- Three species of commonly cultivated indoor plants Philodendron hederaceum, Alocasia amazonica, and Aglaonema modestum were selected based on their popularity in Sri Lankan apartments, varied light tolerance levels, and low maintenance requirements. Each specimen was potted in standardized 12 cm diameter containers containing a growing medium mixture of cocopeat, vermicompost, and river sand in a 2:1:1 ratio. This soil composition was chosen to ensure adequate aeration, drainage, and nutrient balance suitable for indoor plant cultivation.

Experimental Setup and Environmental Control- The trial was conducted within an urban apartment room in Sri Lanka, designed to replicate realistic indoor living conditions. Each plant species was placed within a wooden-framed reflective chamber to ensure even light distribution and minimize external light interference. Three LED

lighting setups were used to represent low (5,000–10,000 lux), medium (15,000–25,000 lux), and high (30,000–40,000 lux) intensity conditions. The artificial lights operated continuously for 24 hours per day to simulate sustained illumination, while a separate control group was maintained outdoors under natural sunlight to serve as a comparative baseline.

Temperature and humidity were carefully regulated to maintain stable interior conditions, with temperature levels ranging from 24°C to 28°C and relative humidity between 45% and 65%. These parameters reflect typical apartment microclimates in tropical urban contexts. Regular monitoring ensured that all test conditions remained consistent across the experiment.

Data Collection and Observation Parameters- Data were collected through systematic observation twice daily over the 14-day period. Quantitative measurements included plant height, number of leaves, and leaf area expansion, which were recorded using a standardized scale and digital caliper for accuracy. Qualitative assessments focused on visual indicators such as leaf color, texture, and the presence of stress symptoms including wilting, discoloration, or pest infestation. Particular attention was given to detecting scale insect presence in Aglaonema modestum and chlorosis in Alocasia amazonica, as these were early indicators of lighting stress.

Through this controlled experimental procedure, the study aimed to identify optimal artificial light intensities that promote healthy vegetative growth while minimizing stress in common indoor plants. The collected data provided a foundation for evaluating how light intensity can be effectively managed within biophilic interior design strategies to support both ecological sustainability and occupant well-being.

3. RESULTS AND DISCUSSION

The qualitative observations examined the visual growth response of *Aglaonema modestum*, *Philodendron hederaceum*, and *Alocasia amazonica* under varying artificial light intensities. Morphological changes such as leaf color, variegation, and texture were recorded throughout the 14-day experiment. The overall growth differences among the three species are illustrated in **Figure 1,** which presents their qualitative characteristics under controlled indoor conditions.

Aglaonema modestum exhibited enhanced leaf coloration and variegation under medium-intensity lighting, suggesting optimal photosynthetic activity. However, high-intensity exposure led to leaf curling and minor insect infestation, while low-intensity light produced slower growth and faded variegation. *Philodendron hederaceum* showed slower leaf development and tip browning under medium light, but faster growth and richer green pigmentation under high light, though slight edge yellowing indicated mild stress.

Alocasia amazonica displayed sensitivity across all light levels, showing signs of wilting and discoloration at medium and high intensities, confirming its preference for shaded environments. Overall, medium light intensity produced the most stable and visually appealing growth, particularly for *Aglaonema modestum*. These findings highlight the importance of selecting appropriate artificial light levels in apartment interiors to support plant vitality and enhance biophilic design outcomes.

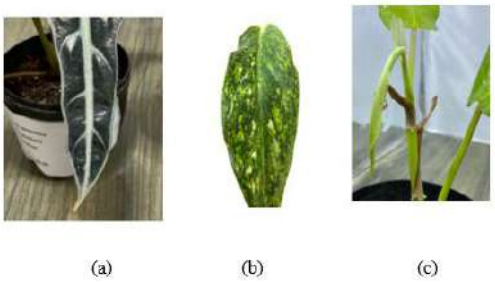

Fig. 1. Visual observation of selected *Araceae* species used in the study (a) *Alocasia amazonica*, (b) *Aglaonema modestum*, and (c) *Philodendron hederaceum* demonstrating qualitative growth characteristics under indoor conditions.

Plant Height under Different Light Conditions- The study compared the variation in plant height of Philodendron hederaceum and Aglaonema modestum under four lighting conditions low, medium, high, and natural sunlight over a 14-day period. At the start of the experiment, all plant samples were standardized to a height of 20 cm to ensure uniformity. Over time, Aglaonema modestum showed optimal height increase under low and medium LED light intensities, while Philodendron hederaceum demonstrated greater vertical growth under medium and high light levels (Figure 2 and Figure 3). These findings indicate that moderate light levels promote stable growth, while excessive illumination may accelerate elongation but risk inducing stress symptoms

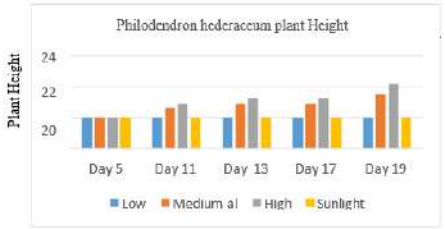

Fig: 2Variation in Philodendron hederaceum plant height measured under four lighting conditions, low, medium, high, and natural sunlight, over a 14-day observation period

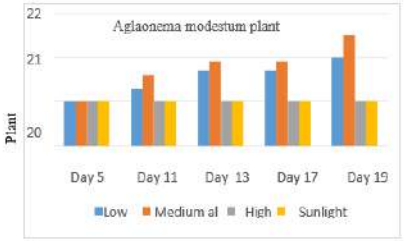

Fig: 3 Variation in Aglaonema modestum plant height measured under four lighting conditions, low, medium, high, and natural sunlight, over a 14-day observation period.

Number of Leaves under Different Light Conditions- Leaf count analysis revealed that plants grown under artificial LED lighting exhibited a notable increase in leaf number compared to those exposed to natural sunlight. This suggests that regulated artificial lighting supports higher vegetative activity and adaptability by providing consistent light exposure. In contrast, plants under natural light displayed minimal or negative changes, likely due to environmental stress and fluctuating sunlight intensity. The comparative results before and after the experiment are illustrated in Figure 4 and Figure 5, respectively.

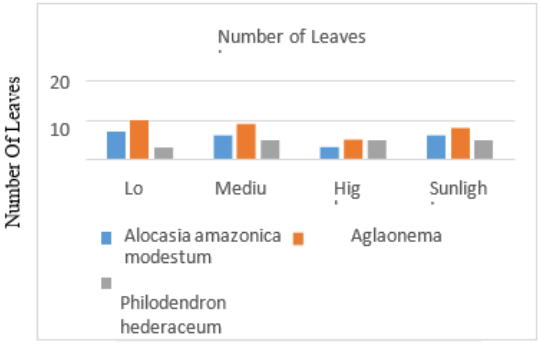

Fig. 4. Number of leaves of three *Araceae* species under different lighting conditions before the experiment.

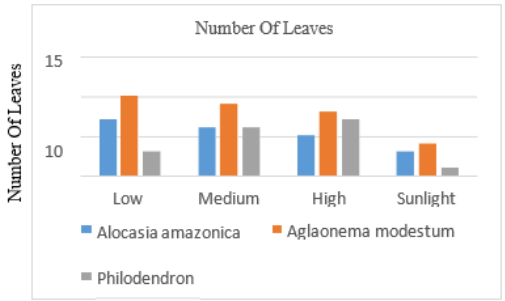

Fig. 5. Number of leaves of three *Araceae* species under different lighting conditions after the experiment.

Leaf Area Across Light Conditions- The comparison of leaf area among Alocasia amazonica, Aglaonema modestum, and Philodendron hederaceum under varying artificial lighting intensities demonstrated a strong positive response to medium LED light levels (Figure 6 and 7). Plants under natural sunlight produced smaller leaves, likely due to direct heat exposure, inconsistent light duration, and partial leaf desiccation. Conversely, indoor plants under regulated artificial light exhibited broader and healthier leaf surfaces, indicating more efficient photosynthetic activity and optimal growth performance in controlled interior environments.

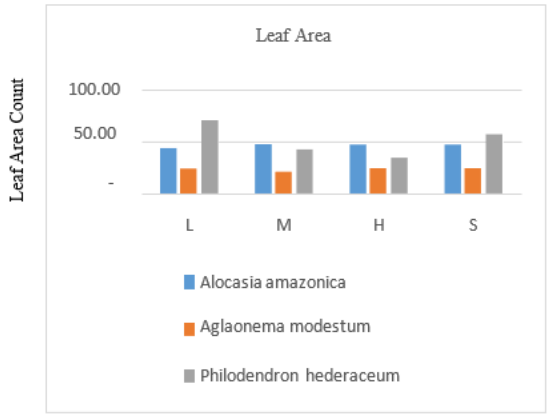

Fig. 6. Comparison of leaf area in three *Araceae* species (*Alocasia amazonica*, *Aglaonema modestum*, and *Philodendron hederaceum*) under varying artificial lighting intensities (Low, Medium, High).

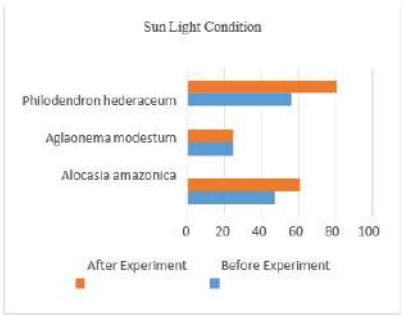

Fig. 7. Comparison of leaf area in three *Araceae* species (*Alocasia amazonica*, *Aglaonema modestum*, and *Philodendron hederaceum*) under natural sunlight conditions.

4. FINDINGS

The findings of this study propose a practical biophilic lighting strategy for apartment interiors that integrates both human visual comfort and plant health requirements. The results indicate that a combined lighting approach utilizing photosynthesis-supportive task lighting alongside ambient warm white illumination can effectively sustain indoor vegetation while maintaining a visually pleasant environment for occupants.

This dual-purpose lighting configuration allows artificial light to serve both aesthetic and functional objectives. The photosynthetic task lighting ensures that plants receive the optimal light spectrum and intensity necessary for healthy growth, while the ambient warm white lighting contributes to a comfortable and psychologically soothing atmosphere, reinforcing the principles of biophilic design. Importantly, this solution can be implemented within existing apartment structures without major modifications or the need for specialized horticultural grow lights.

By balancing ecological and human-centered design considerations, the proposed system enhances the integration of nature within compact residential environments. It promotes sustainable indoor greenery maintenance, improves indoor environmental quality, and supports the psychological well-being of occupants, demonstrating how biophilic lighting can be both an aesthetic and functional design innovation for urban apartments.

5. CONCLUSION

This study examined the application of biophilic design principles in apartment interiors, emphasizing the relationship between indoor vegetation and artificial lighting conditions. The research demonstrated that biophilic elements, such as indoor plants, natural materials, and well-calibrated lighting play a vital role in enhancing both environmental quality and human well-being within compact residential spaces. Through controlled experimentation, the successful implementation of direct biophilic strategies was observed, particularly in the use of artificial lighting to sustain plant growth and maintain visual comfort. The findings revealed that LED lighting, when applied with appropriate intensity and spectral balance, significantly improves plant health, promoting leaf development and overall vitality. This confirms that lighting is not only an aesthetic consideration but also a critical environmental factor in sustaining indoor ecosystems. Moreover, the results reinforce that moderate artificial lighting can effectively substitute for natural light in apartment settings, supporting plant photosynthesis while maintaining occupant comfort.

From a design perspective, these outcomes provide valuable guidance for interior designers and architects seeking to integrate nature-based solutions into modern living environments. The adoption of dual-purpose lighting serving both visual and vegetative functions presents an efficient and sustainable approach to biophilic design. Ultimately, this study underscores the potential of integrating artificial lighting systems that enhance both plant performance and human experience, contributing to healthier, more sustainable, and psychologically restorative apartment interiors.

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Role of Modular and Off-site Construction in Sri Lanka's Post-COVID Recovery

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Abstract— The COVID-19 pandemic accentuated longstanding inefficiencies in Sri Lanka's construction sector by triggering widespread workforce disruptions, prolonged site closures, supply chain breakdowns, and significant project delays that threatened both economic stability and infrastructure development goals. In contrast, global experiences have shown that modular and off-site construction (OSC) can deliver rapid, high-quality, and resilient building solutions under emergency conditions, minimizing on-site labor requirements and enhancing quality control. This study investigates the potential for OSC to support Sri Lanka's post-pandemic recovery by assessing current industry awareness, evaluating the performance of pilot implementations, exploring stakeholder perceptions, and examining policy readiness. A mixed-methods design was adopted, integrating a structured online survey of 72 industry professionals, semi-structured interviews with 14 key informants (including contractors, regulators, and academics), and a detailed analysis of two recent pilot projects (a modular classroom expansion and a prefabricated healthcare facility). Results demonstrate that OSC approaches can shorten project timelines by over 35%, reduce labor costs by approximately 20–36%, and lower construction waste by more than 70%, while also improving safety and environmental outcomes. However, adoption is constrained by limited local technical expertise, high upfront capital requirements, regulatory inertia, and cultural resistance to non-traditional methods. Drawing on the best international practices and local evidence, we propose a phased roadmap and targeted policy recommendations. These include regulatory reform, financial incentives, capacity building, demonstration projects, and stakeholder engagement to accelerate OSC uptake, enhance resilience, and position Sri Lanka's construction industry for sustainable growth in a post-pandemic context.

Keywords— Modular Construction, Off-site Construction, Policy, Post-COVID Recovery, Sri Lanka

1. INTRODUCTION

The COVID-19 pandemic, beginning in early 2020, disrupted economies and societies globally. In Sri Lanka, where the construction sector contributes roughly 7–9% of GDP and employs hundreds of thousands directly and indirectly, lockdowns and mobility restrictions led to widespread site closures, labor shortages, supply chain interruptions, and financial instability among contractors [1], [2]. Over 45% of ongoing projects reported significant delays or suspensions during the first eighteen months of the pandemic, which sharply exacerbated pre-existing challenges such as chronic project overruns, dependence on manual labor, material wastage, and slow uptake of digital and industrialized methods [1], [3].

Modular and off-site construction (OSC), characterized by factory-based prefabrication of building components or full volumetric modules followed by on-site assembly, has demonstrated substantial resilience and efficiency gains during recent crises globally. For instance, rapid completion of emergency hospitals in China and the UK during COVID-19 highlighted OSC's ability to deliver critical infrastructure within days [4], [5]. By decoupling the bulk of construction activities from on-site uncertainties, such as weather, labor availability, and site constraints, OSC offers improved quality control, shorter schedules, reduced waste, and safer working environments, attributes highly relevant to Sri Lanka's post-pandemic recovery. Yet, despite isolated pilots showing promise, Sri Lanka's OSC adoption remains nascent, hindered by limited industrial capacity, scarce technical expertise, regulatory frameworks tailored to conventional methods, high upfront investments, and cultural conservatism within the sector [2], [6].

This study addresses four central questions: first, what is the current landscape of OSC awareness, readiness, and adoption in Sri Lanka's construction industry? Second, how do modular and off-site methods compare to traditional construction regarding cost, schedule, quality, safety, and environmental performance, particularly under crisis conditions? Third, what are the primary barriers, technical, financial, regulatory, and cultural —that constrain OSC integration in Sri Lanka? Fourth, which policy frameworks, capacity-building efforts, and demonstration projects can effectively facilitate scaling up OSC for national recovery and long-term resilience? To answer these, we employ a mixed-methods approach combining an industry survey, expert interviews, and pilot project performance analysis. Drawing on international literature and local case studies, we critically assess OSC readiness and propose actionable recommendations. The remainder of this paper is organized as follows: Section 2 reviews OSC concepts, enabling technologies, and international experiences during COVID-19; Section 3 outlines Sri Lanka's construction industry landscape, pandemic impacts, and early OSC pilots; Section 4 describes the research methodology; Section 5 presents results; Section 6 discusses implications and outlines a phased roadmap; Section 7 concludes with key findings and suggestions for future research..

2. LITERATURE REVIEW

2.1 Conceptual Foundations of Modular and Off-site Construction

Modular and off-site construction (OSC) refers to processes in which significant building components, such as structural panels, volumetric modules, or complete rooms, are manufactured under controlled factory conditions and subsequently transported to the site for assembly [3], [7]. This industrialized approach contrasts with traditional in-situ construction, which relies heavily on manual labor and site-based processes subject to weather, site constraints, and workforce variability. OSC leverages standardization, rigorous quality assurance, lean production principles, and digital design-to-fabrication workflows to deliver improved outcomes in time, cost, quality, safety, and sustainability.

2.1.1. Definition and Scope

Volumetric modular units equipped with finishes, mechanical, electrical, and plumbing (MEP) services, and fixtures [3]. Various terms appear in global literature: "industrialized building systems (IBS)," "modern methods of construction (MMC)," and "prefabrication," all of which emphasize off-site manufacturing as the core principle [7], [8]. By migrating labor-intensive tasks into factory environments, OSC enables parallel

workflows, allowing site preparation to proceed concurrently with module fabrication, thereby shortening overall project schedules.

2.1.2. Historical Evolution

Though prefabrication dates back to early 20th-century housing and wartime reconstruction efforts, modern OSC has been propelled by technological advancements, sustainability imperatives, and productivity stagnation in construction over recent decades [3]. In developed economies, Japan's post-WWII mass housing, Scandinavian modular housing, the UK's public housing programs, and Singapore's public housing programs have gradually institutionalized [8], [9]. The COVID-19 pandemic further accelerated interest by demonstrating OSC's capacity for rapid emergency response through the delivery of healthcare facilities within days [4], [5].

2.1.3. Enabling Technologies and Innovations

Digital design tools, notably Building Information Modeling (BIM), facilitate precise three-dimensional modeling, clash detection, and coordination between design and factory fabrication [3], [10]. Advanced manufacturing technologies, such as computer numerical control (CNC) cutting, robotic assembly, and automated material handling systems, enhance precision and throughput in module production [7], [11]. Lean manufacturing principles adapted from industrial engineering optimize production flows, reduce waste, and improve efficiency [7]. Sustainability considerations drive the use of low-carbon materials and energy-efficient manufacturing processes, while OSC's potential for disassembly and reuse aligns with circular economy objectives [5], [7]. Recent advancements in digital twins and IoT for asset management further bolster the case for OSC [12], [13].

2.1.4. Value Proposition of OSC

Advocates highlight several advantages of OSC. First, accelerated project delivery arises from parallel site and factory workflows, often shortening schedules by 30-50% [4], [7]. Second, quality control improves through standardized factory inspections and testing, reducing defects and rework. Third, enhanced worker safety results from relocating tasks into controlled environments, lowering accident rates. Fourth, environmental performance benefits from reduced material waste, often by over 75%, and lower embodied energy through optimized production processes [5], [7]. Finally, OSC's modularity and flexibility enable rapid reconfiguration or scaling, essential for emergency response and evolving demands [4]. These attributes have been confirmed in diverse sectors, such as residential, commercial, healthcare, and educational facilities, especially under the pressures of the COVID-19 crisis.

2.2 OSC in the Global Context and COVID-19 Acceleration

Before the pandemic, OSC adoption varied across regions. Developed markets like Sweden, Finland, the UK, Japan, and parts of North America had institutionalized modular techniques, particularly in housing and public infrastructure [8], [9]. Key drivers included urbanization pressures outpacing traditional methods, labor shortages prompting factory-based processes, and sustainability imperatives demanding resource-efficient systems [4], [7]. In emerging economies, interest existed, but industrial capacity and policy incentives were often insufficient for widespread uptake.

2.2.1. Pandemic as Catalyst

The onset of COVID-19 created urgent needs for rapid delivery of healthcare facilities, emergency accommodations, and safer working environments. In China, the Huoshenshan and Leishenshan hospitals in Wuhan were completed in approximately 10 to 12 days using modular systems [4]. In the UK, Nightingale hospitals were swiftly erected via prefabricated components [5]. Singapore leveraged its Prefabricated Prefinished Volumetric Construction (PPVC) mandate to accelerate healthcare and housing projects, achieving notable build-time reductions [6]. In the US, modular housing production is scaled up to meet urgent accommodation demands. McKinsey & Company reported a roughly 30% global increase in modular projects during the pandemic, especially in healthcare, education, and residential sectors [4]. These experiences underscored OSC's agility in crisis response and shifted industry mindsets toward industrialized, resilient construction models [14].

2.2.2. Synthesized Benefits and Lessons

Global evidence consistently highlights OSC advantages: projects completed 30-50% faster due to parallel workflows; although initial factory investments are higher, lifecycle costs often decrease via reduced labor, minimized rework, and waste savings [4], [7]; quality and safety improve in factory-controlled settings; environmental performance benefits from significantly reduced waste and energy consumption [5], [7]; and modular flexibility supports rapid adaptation to changing needs. Nevertheless, widespread adoption also revealed challenges: complex logistics in transporting large modules, high upfront capital requirements for manufacturing facilities, supply chain coordination demands, regulatory gaps lacking OSC-specific standards and expedited approvals, and cultural resistance among stakeholders unfamiliar with modular methods [4], [6], [9]. Successful mainstreaming of OSC has often depended on enabling policy frameworks, strong industry collaboration, and sustained investment in skills and technology.

2.3 Sri Lankan Construction Industry: Pre-Pandemic Characteristics and COVID-19 Impacts

Sri Lanka's construction sector, contributing around 7-9% of GDP and supporting hundreds of thousands of jobs, has historically driven infrastructure growth and urbanization [8]. However, structural inefficiencies were prevalent before COVID-19: project overruns and cost escalations affected 30-40% of large-scale projects; manual labor dependence and limited mechanization and digitalization hindered productivity; high material waste contributed significantly to solid waste streams; and OSC or other industrialized methods saw minimal uptake due to scarce local capacity and awareness [2], [3], [10].

2.3.1. Pandemic Disruptions

Beginning in early 2020, lockdowns and health restrictions forced widespread site closures, with over 45% of projects suffering significant delays or suspensions [1]. Labor shortages emerged as workers returned to rural areas; remobilization post-lockdown proved slow and costly. Supply chain disruptions impeded material imports and equipment deliveries, inflating costs and further delaying works. Contractors, especially small and medium enterprises, faced cash flow interruptions and financial instability. New health and safety protocols increased operational expenses and reduced productivity. These compounded effects revealed the sector's vulnerability to

disruptions and underscored the need for more resilient, less labor-intensive models [1], [2].

2.3.2. Early OSC Pilots in Sri Lanka

In response to pandemic pressures, isolated OSC experiments emerged in Sri Lanka. Jayawardana et al. conducted a pilot case study assessing prefabricated construction's sustainability potential, demonstrating time savings and slight reductions in greenhouse gas emissions compared to traditional methods [1]. Munmulla et al. surveyed practitioners on modular technology for house construction, finding that modular approaches yielded approximately a 32% reduction in total construction costs, a 36% reduction in labor costs, and around a 16% reduction in embodied energy for a single-story house case study [2]. Private-sector initiatives, especially firms with multinational affiliations, trialed modular office blocks and warehouses to improve speed and cost control. Nevertheless, fewer than 20% of large contractors reported substantive OSC experience, and most professionals viewed OSC as experimental or risky within the local context [1], [2].

2.3.3. Policy and Institutional Context

Sri Lanka's regulatory framework remains oriented toward conventional site-based construction. Building codes and approval processes under the Urban Development Authority (UDA) and Sri Lanka Standards Institution (SLSI) lack explicit OSC provisions, such as modular system performance criteria, factory inspection protocols, or standardized installation guidelines [1]. Consequently, OSC projects face protracted review times, often six to eight months longer than conventional builds due to regulatory unfamiliarity [1]. Certification schemes for modular factories and prefabricated products are absent, raising concerns about consistency and accountability. Post-COVID recovery programs prioritized credit relief and wage support but did not specifically incentivize technological innovation or OSC adoption. These gaps reinforce industry conservatism and deter investments in OSC capacity [1], [6].

2.4 Barriers and Enablers for OSC Adoption in Sri Lanka

Interrelated barriers and potential enabling factors shape Sri Lanka's OSC transition.

2.4.1. Barriers

A primary barrier is the technical and skills deficit: most professional engineers, architects, and site supervisors lack hands-on experience with modular design, digital fabrication, and industrialized workflows, as academic and vocational curricula focus on conventional methods [2], [3]. The scarcity of local suppliers and manufacturers capable of producing high-quality prefabricated modules often forces reliance on imports or discourages OSC altogether. High initial capital investment poses another significant hurdle: establishing modular factories, acquiring advanced machinery, and training personnel require substantial upfront funding, which many small and medium enterprises find prohibitive under uncertain economic conditions [1], [2]. Regulatory and policy constraints further impede adoption: building codes and approval processes lack OSC-specific standards and fast-track pathways, resulting in ambiguity and extended review times [1]. Cultural resistance and industry conservatism fuel perceptions of OSC as risky or unproven in the Sri Lankan context, reinforced by limited local success stories [1]. Logistical and supply chain challenges, the transportation of

large modules across varied terrain and through urban areas, and inconsistent material quality add complexity and cost.

2.4.2. Enablers

Despite these barriers, several factors can enable OSC uptake. Supportive policy and regulatory reform are crucial: developing OSC-specific technical standards, establishing fast-track approval mechanisms, and offering fiscal incentives (tax holidays, grants, concessional loans) can mitigate perceived risks and signal government commitment [6], [7]. Public-private partnerships and high-visibility demonstration projects in public infrastructure (schools, clinics, social housing) can showcase the viability of OSC in the local context, generate case studies, and build industry confidence [1], [2]. Capacity building and academic engagement are essential: integrating OSC topics into university and vocational curricula, funding targeted upskilling workshops, and fostering research collaborations equip the workforce with necessary skills [2], [3]. International collaboration and technology transfer through partnerships or joint ventures with established OSC firms from Singapore, China, the UK, and other markets can accelerate knowledge exchange and development of local supplier networks [6], [9]. Finally, post-pandemic recovery imperatives create market demand for rapid, safe, and scalable solutions, making OSC an increasingly attractive option for both public and private clients.

2.5 Economic, Environmental, and Social Impacts of OSC

Global research and Sri Lankan pilot evidence indicate that OSC delivers multifaceted benefits.

2.5.1. Economic Impacts

OSC enables accelerated project delivery by decoupling site preparation from module fabrication, often reducing schedules by 30–50% [4], [7]. In Sri Lanka, Munmulla et al. reported a 32% reduction in total construction costs and a 36% reduction in labor costs for a modular house compared to conventional construction [2]. Though initial factory investments are higher, lifecycle cost savings arise from reduced labor requirements, minimized delays, and lower waste management expenses. OSC introduces standardized, repeatable processes that enhance productivity and create new opportunities in manufacturing, logistics, and related sectors. As OSC capacity develops, Sri Lanka could position itself to export prefabricated components to regional markets, supporting sector diversification and foreign exchange earnings [8].

2.5.2. Environmental Impacts

Factory-based production is inherently more efficient in material usage than on-site construction. Global evidence shows that OSC can reduce construction waste by 75–90% [5]. Sri Lankan studies highlight the construction sector's significant contribution to solid waste streams, underscoring the environmental imperative for waste minimization. Munmulla et al. observed around 16% reduction in embodied energy for a modular house versus conventional methods [2]. Controlled fabrication and improved building performance, such as tighter tolerances and better thermal insulation, yield lower operational energy consumption. OSC modules can be designed for disassembly or reuse, aligning with circular economic principles and further reducing lifecycle

impacts [5]. Shortened on-site durations also reduce local disturbances, noise, dust, and emissions.

2.5.3. Social Impacts

Worker safety improves markedly as factory-based environments mitigate many on-site hazards; during the pandemic, OSC enabled social distancing and reduced viral transmission risk [4]. Sri Lankan pilots recorded zero lost-time injuries for OSC projects, unlike incidents in conventional projects [1]. OSC creates new job categories in digital design, factory operations, logistics, and module assembly, broadening employment opportunities and potentially engaging underrepresented groups in less physically demanding factory roles. Rapid OSC deployment supports emergency response healthcare facilities or temporary shelters, enhancing social resilience. While initial community skepticism may occur, transparent communication and demonstration of OSC benefits can build trust in faster, cleaner construction processes.

2.6 Policy, Standards, and Pathways for OSC Adoption

International experience shows that coordinated policy frameworks, technical standards, and incentives are vital for mainstreaming OSC.

2.6.1. Current Sri Lankan Regulatory Environment

Sri Lanka's regulatory framework under UDA and SLSI remains oriented toward conventional methods, lacking explicit provisions for OSC, modular system performance, factory inspection protocols, or installation guidelines [1]. Approval processes lack fast-track pathways for OSC, resulting in extended review times and uncertainty. Certification schemes for modular factories and prefabricated products are absent, undermining stakeholder confidence. Post-COVID recovery programs have focused on financial relief for contractors but have not prioritized OSC or technological innovation.

2.6.2. International Policy Models

Singapore's Prefabricated Prefinished Volumetric Construction (PPVC) mandate requires a minimum prefabrication level for public housing. It is supported by fast-track approvals, performance-based standards, and subsidized training, achieving substantial build-time reductions [6]. The UK's Construction Playbook promotes Modern Methods of Construction (MMC) through public procurement preferences, industry accreditation, and clear technical guidelines [7]. Malaysia's Industrialized Building System (IBS) framework offers tax incentives, government-led pilot projects, and certification programs. India's housing schemes provide subsidies for prefab housing for low-income groups. These models illustrate that regulatory clarity, market incentives, capacity building, and government leadership are critical for OSC mainstreaming.

2.6.3. Recommended Pathways for Sri Lanka

A phased, integrated strategy is proposed:

First, regulatory reform must prioritize the development of OSC-specific technical standards. UDA and SLSI should collaborate to formulate guidelines covering the structural performance of modules, factory quality assurance practices, and standardized on-site assembly protocols. Concurrently, a fast-track approval mechanism within UDA staffed by personnel trained in OSC review and operating under explicit

timelines (e.g., 90 days) would reduce uncertainty and encourage investment. A mandatory certification scheme for modular factories and prefabricated products would ensure consistent quality benchmarks.

Second, financial incentives and market stimulation are essential. Multi-year tax holidays and concessional financing should be offered to firms establishing modular factories or engaging in OSC innovation. Public procurement leadership can mandate or strongly prefer OSC methods for a proportion of government-funded buildings (schools, clinics, social housing), ensuring reliable demand and fostering industry capacity. Grants or subsidies for initial demonstration pilots will generate local case studies and performance data, further reducing perceived risk.

Third, capacity building must be addressed through academic engagement: OSC topics should be integrated into university and vocational curricula, and funding should be allocated for industry-led upskilling workshops, certification courses, and collaborative research on OSC technologies, local materials, and business models. Such efforts equip graduates and existing professionals with skills in modular design, digital fabrication, lean manufacturing, and factory management.

Fourth, stakeholder engagement and awareness activities are critical. High-visibility demonstration projects should be commissioned and their outcomes (time, cost, quality, safety, environmental metrics) disseminated widely through industry forums, publications, and site visits. Regular consultation workshops involving contractors, architects, engineers, developers, and regulators will foster buy-in and provide feedback loops for refining standards and processes. Transparent communication of pilot results helps shift cultural resistance.

Fifth, international collaboration offers pathways for technology transfer and knowledge exchange. Partnerships or joint ventures with experienced OSC firms from Singapore, China, the UK, and other markets can bring expertise in design methodologies, manufacturing workflows, logistics planning, and digital integration. By benchmarking global best practices and iteratively adapting them to Sri Lanka's regulatory, economic, and cultural context, we ensure their relevance and feasibility.

Long-term strategy should integrate OSC into national infrastructure and development master plans, exploring export opportunities for prefabricated components to neighboring markets. Continuous monitoring of environmental and socio-economic impacts will inform policy refinements, aligning OSC growth with circular economic objectives, such as module disassembly and reuse. Investment in advanced digital and automation technologies further enhances OSC productivity and quality. This phased approach, where each stage builds on previous foundations, can transform Sri Lanka's construction sector into a resilient, efficient, and globally competitive industry.

2.7 Research Gaps and Rationale

Existing literature on OSC largely addresses high-income economies, with limited rigorous analyses for small island developing states like Sri Lanka. The systematic evaluation of local pilot projects across cost, schedule, quality, safety, and environmental metrics is either scarce or unpublished. Stakeholder perceptions and readiness for OSC integration have not been comprehensively studied, and policy pathway analyses adapted to Sri Lanka are lacking. Furthermore, few studies employ an integrated mixed-methods approach combining survey data, interviews, and pilot performance analysis to

provide holistic insights. Given the urgency of post-pandemic recovery and the nascent nature of OSC in Sri Lanka, this study fills these gaps by conducting a structured survey of industry professionals, in-depth interviews with key informants, and a detailed analysis of two recent pilot projects, culminating in evidence-based recommendations for policy, capacity building, and sectoral transformation.

3. METHODOLOGY

A concurrent mixed-methods design was adopted to triangulate quantitative and qualitative data, ensuring a comprehensive understanding of OSC's potential and challenges in Sri Lanka's post-pandemic context. The approach integrates an industry survey, semi-structured interviews, and pilot project performance analysis.

3.1 Research Design Overview

The mixed-methods approach captures measurable outcomes from pilot projects and survey data on perceptions, while in-depth interviews provide nuanced insights into stakeholder attitudes. Triangulation enhances validity and practical relevance.

3.2 Data Collection Methods

3.2.1. Industry Survey

A structured online questionnaire comprising 27 items (including multiple-choice, Likert-scale, and open-ended questions) was developed to assess familiarity with OSC, perceived advantages and disadvantages, barriers and enablers, policy/regulatory awareness, and willingness to engage in OSC projects. The survey was disseminated via professional bodies (IQSSL, IESL), LinkedIn groups, and direct email invitations. Of approximately 110 invitations, 72 complete responses were received (65% response rate). The response percentages are mentioned in Table 1 below.

Table 1- Survey Respondent Profile

Role	Percentage (%)
Contractor / Project Manager	39
Engineer / Architect	28
Policymaker / Regulator	18
Academic / Researcher	15

3.2.2. Semi-Structured Interviews

To contextualize survey findings, we conducted 14 in-depth interviews with key informants: senior contractors and project managers involved in OSC or pilot projects, regulatory officials from UDA and the Ministry of Urban Development, and academics/consultants specializing in construction innovation. Each interview, lasting 45–70 minutes, followed a semi-structured guide covering experiences with OSC implementation, perceptions of regulatory, financial, technical, and cultural barriers, and

views on required policy reforms and capacity building. Interviews were recorded (with consent), transcribed, anonymized, and thematically coded using both deductive (based on literature and survey themes) and inductive (emergent insights) approaches. Thematic saturation was determined to have been reached after approximately 12 interviews, as subsequent interviews yielded no new substantive themes.

3.2.3. Pilot Project Performance Analysis

Two recent OSC pilot projects in Sri Lanka were selected for detailed analysis based on the following criteria: recency (completed 2021-2023), project type (educational and healthcare), and accessibility of comprehensive data. The projects were a modular classroom expansion in Colombo (2021-2022) and a prefabricated healthcare facility in Kandy (2022-2023). Data was sourced from project reports, contractor records, site visits, and discussions with project managers. Extracted metrics included project timelines and phases, on-site versus off-site labor hours, material usage and waste generation, total project costs (direct and indirect), safety incident records, and energy and water consumption. Comparable traditional projects of similar scale and function were identified for benchmarking.

3.3 Data Analysis Procedures

3.3.1. Quantitative Analysis

Survey responses underwent descriptive statistical analysis, including frequency distributions, means, and standard deviations for Likert-scale items, and cross-tabulations to explore relationships between respondent demographics and perceived barriers/enablers. Pilot performance data were benchmarked against traditional projects via percentage change calculations for schedule, labor, waste, cost, and environmental metrics.

3.3.2. Qualitative Analysis

Interview transcripts were coded thematically using qualitative analysis software to identify recurring patterns and salient themes related to OSC readiness, barriers, and enablers. Triangulation cross-referenced qualitative insights with survey findings and pilot data to highlight convergences and divergences.

3.4 Validity, Reliability, and Limitations

Validity is enhanced through methodological triangulation; pilot project data provide objective measures while surveys and interviews capture perceptions. Reliability was addressed by pre-testing the survey instrument with five professionals to ensure clarity and relevance, and by employing standardized interview protocols. This study has several limitations. The generalizability of findings is constrained by the relatively small interview sample size (n=14) and the analysis of only two pilot projects. The survey, while achieving a 65% response rate, may be subject to non-response bias, as those interested in OSC might have been more likely to participate. The geographic scope of the pilots (Colombo and Kandy) may limit applicability to other regions in Sri Lanka or other developing contexts. Therefore, broad conclusions should be drawn with caution. Nonetheless, the study offers robust evidence for policy and industry decision-making in similar developing contexts.

3.5 Ethical Considerations

Participants provided informed consent and were assured of anonymity and confidentiality. Data was securely stored and reported in aggregate form to prevent identification.

4. RESULTS AND DISCUSSION

4.1 Results

4.1.1. Industry Survey Findings

Awareness and Experience with OSC

Only 19% of respondents reported prior hands-on involvement in OSC projects, indicating limited direct experience in the sector. Nevertheless, 68% "agree" or "strongly agree" that OSC could significantly improve project delivery speed and quality in Sri Lanka, and 73% expressed interest in receiving further training or participating in OSC initiatives in the future. This suggests broad recognition of OSC's potential despite low experiential exposure.

Perceived Benefits and Concerns

Respondents most frequently identified faster project delivery as OSC's primary advantage, emphasizing how factory-based prefabrication combined with simultaneous site preparation can substantially shorten schedules. Many also cited reduced on-site labor requirements, improved quality control through standardized factory inspections, and decreased construction waste as significant benefits. Conversely, the foremost concern was the high initial investment costs for establishing or accessing prefabrication facilities. This was followed by a lack of local suppliers capable of producing quality modules, uncertainty in regulatory approval processes for non-traditional methods, and perceived risks regarding the long-term durability of modular components. While practitioners acknowledged OSC's promise, these reservations explain why large-scale adoption may remain cautious without mitigating measures in policy and financing. Table 2 below represents the barriers and enablers identified in the study, along with the responding percentages.

Table 2- Perceived Barriers and Enablers

Category	Item	Percentage (%)
Barrier	High Initial Capital Cost	72
Barrier	Skills Deficit	56
Barrier	Regulatory Uncertainty	49
Barrier	Limited Supplier Network	44
Barrier	Resistance to Change	41

Category	Item	Percentage (%)
Enabler	Government Incentives/Policies	81
Enabler	Demonstration Projects	64
Enabler	Academic / Professional Training	58
Enabler	International Partnerships	52

Barriers and Enablers

When quantifying perceived barriers, approximately 72% of participants regarded high initial capital cost as the principal obstacle to OSC adoption in Sri Lanka, and around 56% highlighted a skills deficit, indicating a lack of training in modular design, digital fabrication, and factory-based workflows. Nearly half (49%) pointed to regulatory uncertainty as a deterrent, and 44% noted the limited supplier network for prefabricated components. Resistance to change within the industry was cited by about 41% of respondents. In terms of enablers, an overwhelming majority (81%) felt that supportive government incentives or policies would be critical to drive OSC uptake; around 64% emphasized the value of demonstration projects to showcase OSC viability; approximately 58% believed academic and professional training programs would facilitate capacity building; and over half (52%) saw international partnerships as important for technology transfer. Thus, while cost and capability gaps loom large, there is consensus that policy support, demonstration initiatives, targeted training, and collaboration can help overcome barriers. Figure 1 below represents the project performance comparison between OSC and the Traditional project.

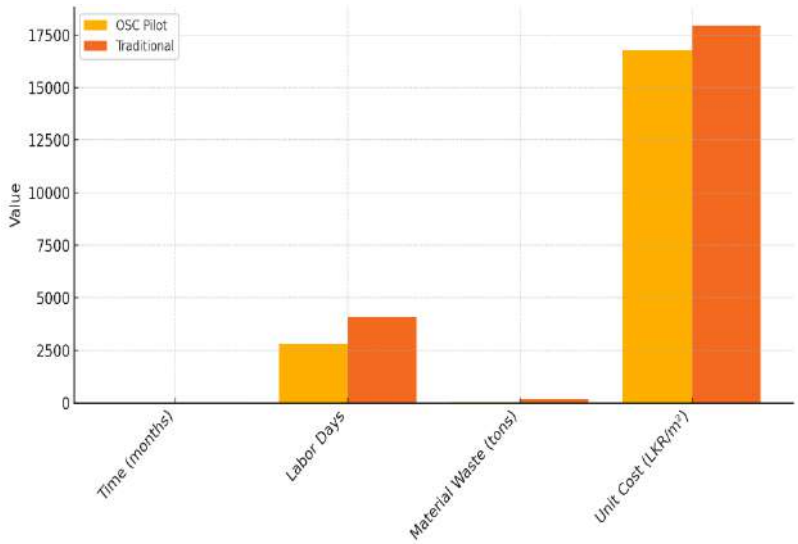

Figure 14- OSC Vs Traditional Project Performance

4.1.2. Qualitative Interview Insights

Stakeholder Perspectives

Contractors and project managers involved in OSC pilots acknowledged the tangible time savings and quality improvements achieved through prefabrication. However, they stressed that a lack of a skilled local workforce, both in factory operations and on-site module assembly, remains a major hurdle. They also pointed to uncertainty surrounding regulatory approvals for modular methods, which adds perceived risk and deters investment in OSC. Policymakers and regulatory officials recognized OSC's potential to accelerate infrastructure delivery and enhance resilience. However, they admitted that current building codes and review processes have not kept pace with these innovations and emphasized the need to upskill regulatory staff and develop clear guidelines. Academics and technical consultants underscored the urgent requirement for curriculum reforms and hands-on training to prepare future professionals for OSC. Across these groups, a tone of cautious optimism prevailed: stakeholders agreed that the post-pandemic environment is more receptive to innovation, yet systemic gaps in skills, finance, regulation, and supply chains must be addressed before OSC can move from isolated experiments to mainstream practice. Figure 2 below illustrates the stakeholder perceptions of OSC benefits, represented by the Likert mean scores.

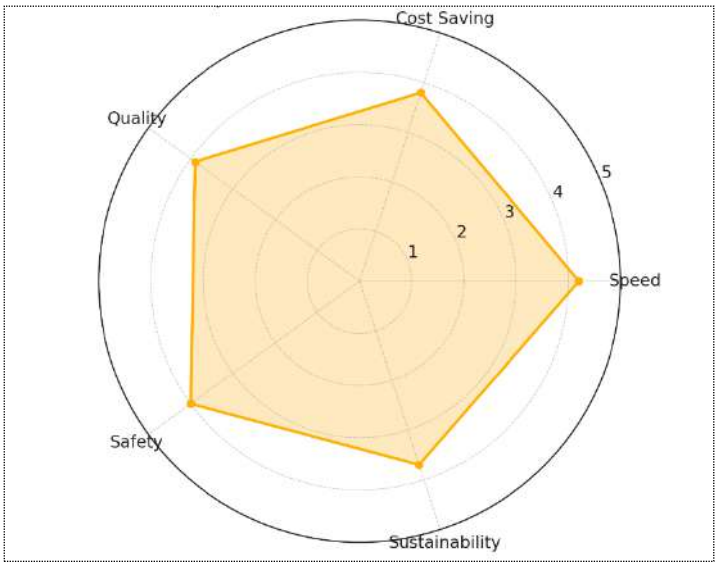

Figure 15- Stakeholder Perceptions on OSC Benefits

Policy and Regulatory Context

Interviewees uniformly noted that current approval times for OSC-related projects often extend six to eight months beyond typical durations for conventional builds, due to regulatory unfamiliarity with off-site methods and lack of tailored procedures. The absence of OSC-specific codes or standards means each project may face bespoke scrutiny, creating uncertainty. Many stakeholders recommended establishing a dedicated "OSC fast-track" pathway within the Urban Development Authority, staffed by personnel trained in modular construction principles and operating under clear

submission requirements and time-bound review timelines. They also advocated developing national technical standards covering modular system design, structural connections, and factory quality assurance protocols, ensuring that industry actors and regulators share a common reference framework that reduces ambiguity and accelerates approvals.

4.1.3. Pilot Project Performance Analysis

Project Delivery and Efficiency

Analysis of the modular classroom expansion pilot in Colombo, compared to a traditional project, revealed that OSC achieved approximately a 36% reduction in build time, completing the project in about 5.2 months versus 8.1 months for the conventional approach. On-site labor days were reduced by around 32%, falling from about 4,100 days in the traditional case to roughly 2,800 days in the OSC pilot. Material waste dropped by approximately 76%, from 173 tons to 42 tons. Despite higher upfront fabrication expenses, the overall unit cost for the OSC pilot was modestly lower (e.g., LKR 16,800/m^2 versus LKR 17,950/m^2) due to savings in labor, rework, and waste management.

Environmental and Health Outcomes

Factory-based module fabrication yielded energy savings of around 40–45% per unit when considering both production efficiencies and improved building performance (thermal insulation and airtightness) compared to conventional on-site construction. Safety records showed zero lost-time injuries (LTIs) in the OSC pilot, whereas the comparable conventional project recorded incidents, confirming improved safety claims. Controlled factory processes enabled systematic waste segregation and recycling, aligning with sustainability objectives.

End-User and Community Feedback

End-users' teachers and healthcare staff in the classroom and clinic pilots reported better indoor environmental quality and faster facility handover, minimizing service disruptions. Initial community skepticism about the "prefabricated" quality dissipated after site visits and the demonstration of finished buildings, with positive word-of-mouth reinforcing trust. Stakeholders noted that transparent communication of performance data (schedule reliability, cost, quality, safety, environmental metrics) helped shift perceptions and build confidence in OSC.

Synthesis of Findings

Triangulation of survey, interview, and pilot data underscores both OSC's promise and the complexity of its adoption in Sri Lanka. Quantitative results confirm substantial gains in efficiency and sustainability consistent with global evidence [4], [5], [7]. Qualitative insights reveal a sector in transition, balancing cautious optimism with real concerns about readiness, regulation, and skills. Stakeholder consensus points to an urgent need for regulatory reform, capacity building, and demonstration initiatives to unlock OSC's potential. International lessons must be adapted to Sri Lanka's regulatory, economic, and cultural realities through iterative pilot-testing and broad stakeholder engagement. Table 3 below represents the pilot project performance comparison.

Table 3- Pilot Project Performance Comparison

Metric	OSC Pilot (e.g., Classroom Exp.)	Traditional Project
Completion Time (months)	5.2	8.1
On-site Labor Days	2,800	4,100
Material Waste (tons)	42	173
Unit Cost (LKR/m^2)	16,800	17,950
Energy Savings (%)	42	-
Lost-Time Injuries	0	3

4.2 Discussion

4.2.1. Relevance and Advantages of OSC for Sri Lanka

Pilot analyses and industry perceptions confirm that OSC delivers benefits directly addressing Sri Lanka's longstanding sectoral pain points: time savings of 30 – 40% accelerate project delivery, labor cost reductions of around 20–36% alleviate workforce shortages, and substantial waste and energy reductions align with national sustainability targets [2], [5]. Enhanced quality control and improved safety in factory environments further strengthen OSC's value proposition. In the aftermath of COVID-19, when conventional labor-intensive practices proved fragile under lockdowns and supply chain disruptions, OSC's resilience and efficiency have moved from desirable enhancements to essential strategies for sector recovery and future proofing.

4.2.2. Addressing Barriers and Leveraging Enablers

The barriers identified are interconnected. The skills deficit (56%) perpetuates regulatory uncertainty (49%), as officials lack trained personnel to review novel systems. Addressing this requires a coordinated "carrot and stick" approach: mandates for OSC in public projects (stick) coupled with training and financial support (carrots). The 65% survey response rate (72 complete responses from 110 invitations) represents adequate coverage of engaged professionals, though non-response bias remains a limitation. High-visibility demonstration projects are powerful tools to build confidence and showcase viability, directly addressing the "resistance to change" (41%).

4.2.3. Implications for Policy and Practice

The strong stakeholder consensus (81%) on the need for government incentives and policy support underscores that market forces alone are insufficient to drive OSC adoption. Regulatory reform is a prerequisite. This includes developing OSC-specific technical standards, establishing a fast-track approval pathway, and creating a certification scheme for modular factories and products. Specific implementation mechanisms could consist of developing a pre-approved list of certified OSC systems,

creating a digital submission portal for OSC projects to streamline reviews, and mandating OSC for a percentage of public sector projects to build market volume.

Financial incentives, such as tax holidays and concessional loans, are crucial to mitigate high upfront costs. Public procurement can create a stable demand pipeline, encouraging private investment in manufacturing capacity. The high interest in training (73% of survey respondents) signals a readiness for upskilling, which academia and professional bodies must address through curriculum integration and targeted workshops.

4.2.4. Stakeholder Engagement and Change Management

Cultural resistance can be overcome through transparent communication and collaborative involvement. Sharing pilot project results, including quantitative data on schedule reliability, cost performance, quality enhancements, safety improvements, and environmental benefits, through industry forums, publications, and site visits helps shift perceptions. Regular workshops and consultations among contractors, architects, engineers, developers, and regulators foster buy-in and refine standards. Demonstration of tangible OSC successes encourages broader adoption. Engaging communities early in the process and addressing quality and durability concerns through visible testing and certifications further builds trust.

4.2.5. Integrating Global Lessons with Local Realities

International successes in Singapore's PPVC mandate [6], the UK's MMC policies [7], Malaysia's IBS incentives, and other models offer inspiration. Still, they must be adapted to Sri Lanka's market scale, economic conditions, and regulatory capacity. Solutions may involve shared or cooperative factory models rather than large single-owner plants, context-appropriate design guidelines for tropical climates, and flexible financing arrangements for SMEs. Pilot testing of adapted practices allows iterative refinement. Developing local materials and designs that align with Sri Lankan cultural preferences enhances acceptability and supply chain feasibility. A phased approach ensures that early learning informs subsequent scaling and that each stage builds upon established foundations.

4.2.6. Phased Roadmap for Sectoral Transformation

Based on evidence and stakeholder inputs, we propose a phased roadmap:

Immediate Term (0–1 year): Mobilize regulatory reform by establishing an OSC task force within UDA and SLSI to draft technical standards and fast-track approval protocols. Commission government-led demonstration pilots (e.g., modular classrooms, rural clinics) to generate local performance data. Initiate curriculum integration workshops with universities and vocational institutes to introduce OSC concepts. Provide seed funding or grants for pilot factory setups, potentially through cooperative facility models that lower entry barriers for SMEs.

Medium Term (1–3 years): Scale financial incentives, offering tax holidays and concessional financing to encourage private-sector investment in modular factories and related technologies. Expand demonstration projects across building types, including social housing and public infrastructure, to develop supply chain networks and accumulate case studies. Strengthening local supplier ecosystems for prefabricated

components through support for SMEs and linkages to materials producers. Forge international partnerships for technology transfer and knowledge exchange, enabling local firms to adopt the best practices in design, manufacturing, logistics, and digital integration. Continue and expand capacity-building programs in academia and industry.

Long Term (3–5+ years): Integrate OSC into national infrastructure and development master plans. Explore export opportunities for prefabricated components to neighbouring markets, leveraging Sri Lanka's strategic location and growing skill base. Invest in advanced digital and automation technologies for OSC productivity and quality enhancements. Implement continuous monitoring and evaluation frameworks focusing on environmental, social, and economic impacts to guide policy adjustments, ensuring alignment with circular economy objectives such as module disassembly and reuse. As domestic capacity matures, a shift toward innovation in sustainable materials and smart factory processes positions Sri Lanka as a regional hub for OSC.This phased approach, where each stage builds on established foundations, provides a structured pathway for transforming Sri Lanka's construction sector into a resilient, efficient, and globally competitive industry. Table 4 below represents the thematic coding summary:

Table 4 - Thematic Coding Summary

Theme	Description / Key Insights	Example Quote (anonymized)
Regulatory Uncertainty	Long approval times, lack of OSC-specific codes	"Approval for the pilot took almost 8 months because there were no clear guidelines."
Skills and Capacity Deficit	Need for training in modular design and factory workflows	"Universities don't teach prefabrication; we must learn on the job."
Perceived Benefits	Time savings, quality improvements	"We saw the project finish 35% faster, with fewer reworks."
Cultural Resistance	Skepticism around durability and quality	"Clients often ask: 'Will this prefabricated building last?'"
Stakeholder Engagement	Importance of demonstration projects and transparent communication	"Site visits to completed pilot changed community perceptions."
Financial Incentives & Funding	Need for concessional loans, tax breaks, subsidies for factory setup	"Without financial support, SMEs cannot invest in a factory."
International Collaboration	Value of partnerships for technology transfer	"Collaboration with a Singapore firm accelerated our learning curve."

5. CONCLUSION

This study provides one of the first comprehensive, mixed-methods evaluations of modular and off-site construction (OSC) in Sri Lanka's post-COVID recovery context. Through an industry survey (n=72), semi-structured interviews (n=14), and pilot project performance analyses, we demonstrate that OSC offers compelling benefits: approximately 35% faster delivery, 20–36% labor cost savings, over 70% waste reduction, enhanced safety, and improved environmental performance. Stakeholder insights reveal cautious optimism tempered by significant barriers: skills shortages, high initial capital requirements, regulatory inertia, and cultural resistance. These challenges are interdependent and require integrated, multi-stakeholder strategies. Government leadership through regulatory reform, procurement policies, and financial incentives is essential. Additionally, academic engagement for capacity building, high-visibility demonstration projects, and international collaborations for technology transfer are crucial. Adapting the best global practices to Sri Lanka's context via iterative pilot-testing and stakeholder involvement will be critical. Sri Lanka stands at a pivotal juncture: the urgency of post-pandemic recovery creates a policy window to catalyze sector modernization. By acting decisively, building on early lessons, fostering cross-sector collaboration, and investing in human and industrial capacity, the construction industry can emerge not only restored but fundamentally reimagined: more resilient, productive, and sustainable for generations to come. Future research should expand pilot analyses across diverse building types, explore financing models for shared OSC facilities, and investigate advanced digital and automation technologies in Sri Lankan OSC contexts.

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Modern Challenges and Future Directions for Hydraulic Infrastructure in Sri Lanka: Engineering, Policy, and Community Perspectives

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Abstract— Sri Lanka has rich hydraulic engineering traditions, remembered in the ancient cascade system of tanks with allowance for sustainable water management over centuries. Even with newer concerns of climate change, acceleration of urbanization, ageing infrastructure, and recongregated government, threatening alarms loom over the sustainability and resilience of Sri Lanka's hydraulic systems today. The research examines these linked concerns and offers feasible options for enhancing Sri Lanka's performance in water infrastructure. The key findings of greatest significance are that rainfall uncertainty, increasing flood frequency, and lengthening drought are triggering impairment of reservoir function and water provision. Urban sprawl has accelerated drainage failure and increased flood hazard, while a water shortage is spreading on both the farm and city sides due to inefficient processes and overdrawing of groundwater. Coastal erosion and rising sea levels caused saltwater intrusion, further degrading water quality. Despite all these concerns, new tools such as integrated water resources management (IWRM), time-series monitoring by hydrologists, sustainable drainage systems (SuDs), and coastal protection through ecosystem services are strong contenders. The research identifies that Sri Lanka's hydraulic infrastructure needs to shift from a crisis-intervention response mode to a proactive, climate-resilient planning approach. The new direction should be to renovate out-of-fad systems, enforce sustainable city design, scale up nature-based strategies, enhance institution-to-institution communication, and facilitate participatory mechanisms for community-managed water management. Investment in research, technology, and awareness will be key for long-term resilience, financial sustainability, and ecological responsiveness of Sri Lanka's water resources.

Keywords—Climate Change, Hydraulic Engineering, Resilience, Water Management

1. INTRODUCTION

Sri Lanka has one of the greatest hydraulic legacies in the world, representing more than two thousand years of innovation and environmental balance, embodied in systems such as the ancient tank cascades and canals, which are still in operation today, demonstrating the level of hydrological knowledge and sustainable construction [1]. The current projects, such as the Mahaweli Development Programme, the Deduru Oya Reservoir, and the Metro Colombo Urban Development Project, have expanded irrigation, increased hydropower, and enhanced flood control, continuing this tradition [2], [3]. The infrastructure, however, is currently grappling with mounting threats from the impacts of climate change, unplanned urbanization, and institutional inefficiencies. Unpredictable precipitation, prolonged droughts, flash floods, sedimentation, and coastal erosion further undermine the water security and soundness of infrastructure

[4], [5], [6], [7]. Urbanization has both enhanced failures to drainage and water pollution [8] and increasing sea level and overexploitation of groundwater have diminished coastal and inland water quality [9], [10]. Moreover, divided governments and vested interests have undermined coordinated water resource management [11]. To deal with these complex challenges, a comprehensive, climate resilient contextual approach would be needed, including the application of sophisticated engineering tools, including real time hydrological monitoring, sustainable urban drainage systems (SUDS), and ecological-based coastal protection systems, coupled with policy reform and community involvement, and this would change the hydraulic system design of Sri Lanka, which is currently designed to react to crises, to a design that is more proactive and able to guarantee long term resilience, sustainability, and national water security [5], [12], [13].

2. METHODOLOGY

Sri Lanka has a rich history of hydraulic engineering, and its ancient water management systems are known to be highly developed and capable of supporting agriculture, settlements, and development of the region over centuries [1], [9], [12]. Such systems as village tank cascades and massive reservoirs represent a high level of knowledge of hydrology and harmony of the ecosystem, in which the water as a source of life is deeply integrated into culture and technology [1], [12]. The water heritage of the country still shapes contemporary ways of governance and management of the resources and sustainable use [11], [14]. But the modern-day Sri Lanka is on the verge of mounting challenges, which are posing a threat to the water systems. The pressures on water resources whether rural or urban have been escalated by rapid urbanization, uncertain climatic condition, mismanagement of land use, and the degradation of hydraulic infrastructure [3], [5], [6], [8]. Moreover, the consequences of climate change, such as the change in rainfall regime and the increase of the sea level, contribute to worsening of the drought, flood, and coastal erosion risks [10], [13]. The combination of these issues is the compelling circumstance that water resources management strategies should be adaptive and integrated. To this end, the literature review explores the development of the hydraulic systems in Sri Lanka, the main issues that are faced by the contemporary water management and the emergent engineering and policy options to provide a viable solution to the problem of ensuring that there is sustainable use of the water resources in this country [2], [11], [15].

2.1 Historical Legacy of Hydraulic Engineering in Sri Lanka

The hydraulic background of Sri Lanka begins with the earliest negotiations around the Anuradhapura Kingdom (377 BC to 1017 AD) and also its outgrowths at the Tambraparni. South India in the Pandian Kingdom negotiation in Sri Lanka (ex-spouse: Aruvi Aru, Malwathu Oya). Several of the systems of the dry area of Sri Lanka, the storage tank falls system (TCS), have been utilized to date as well and have been recommended as a kind of lasting farming [1]. The TCS were plunge systems of tiny storage tanks built in micro-catchments of the completely dry area of the nation, made to capture rain. The dirt on which they were built was of a reduced leak. For this reason, all storage tanks in the falls had an Andal or payment container situated below the bund to permit excess water to drain pipes right into it. Paddy farming depended on rain, and also the building of these storage tanks " taking the features (eg, rain projection instructions as well as rate of the wind as well as wind pressure) to a close to precise understanding". The building and construction of storage tanks in a plunging system ensured the coupling

with the conservation of water and also its fair circulation. The continuous comments between the environmental framework and the feature, as well as disturbance monitoring, were ensured. These old systems, whilst efficient in their time, might not sustain the needs of an expanding populace as well as an altering farming landscape.As the populace of Sri Lanka increased, as well as farming techniques moved, the emphasis changed from small-scale watering systems to large, integrated water source jobs. The Mahaweli Development Programme, started in the 1970s, is one of the most substantial of these contemporary hydraulic projects. [16] explains exactly how the Mahaweli Program aimed to enhance farming and manufacturing, produce hydroelectricity, as well as advertise local growth. The program accomplished substantial success in increasing water and also hydroelectric power; however, likewise triggered substantial environmental impacts such as logging and loss of biodiversity in the upstream basins [2]. This highlighted the requirement for an even more incorporated method to water source administration, that balanced growth with ecological sustainability.

Table 1: Comparison of Ancient and Modern Hydraulic Systems in Sri Lanka

Feature	**Ancient Systems (Tank Cascades)**	**Modern Systems (Mahaweli Programme and Others)**
Main Purpose	Agricultural irrigation	Multipurpose: irrigation, hydroelectricity, development
Technology Level	Indigenous, local knowledge	Engineering and scientific techniques
Environmental Impact	Minimal, sustainable use of water	Significant (deforestation, habitat loss)
Community Involvement	High	Moderate to low
Resilience to Climate Change	Moderate	Under adaptation

2.2 Technological Innovations and Hydraulic Engineering Solutions

Because of the obstacles stated above, numerous advancements in hydraulic design have actually been created coupled with are being executed in Sri Lanka. Among the significant attributes of modern-day water monitoring methods is Integrated Water Resources Management (IWRM). IWRM tries to integrate the contending water needs in between fields such as farming, city water supply, and ecological defence [13]. An instance of IWRM being exercised is the change in the direction of community-based watering monitoring systems in small water plans.[12] shows just how regional engagement in the supply of water has increased water usage performance liability, as well as sustainability. In these systems, choices connected to the supply of water are made at the regional neighbourhood level, which boosts not just effectiveness but also the use of sources in a fashion that proves to be useful to the more comprehensive area.

The second considerable strategy being taken to deal with water source concerns is including environmental durability into hydraulic design. Because environmental adjustment is continuously changing rainfall patterns and also raising the threat of severe events, it has actually become essential to make a framework that can endure such adjustments. [5] go over just how flooding monitoring tasks in Colombo have been changed to represent such adjustments, where designers use environmental designs to forecast future rainfall patterns and also flooding danger. This positive position on the style of hydrodynamics guarantees that the framework stays useful in the face of uncertain climate patterns.

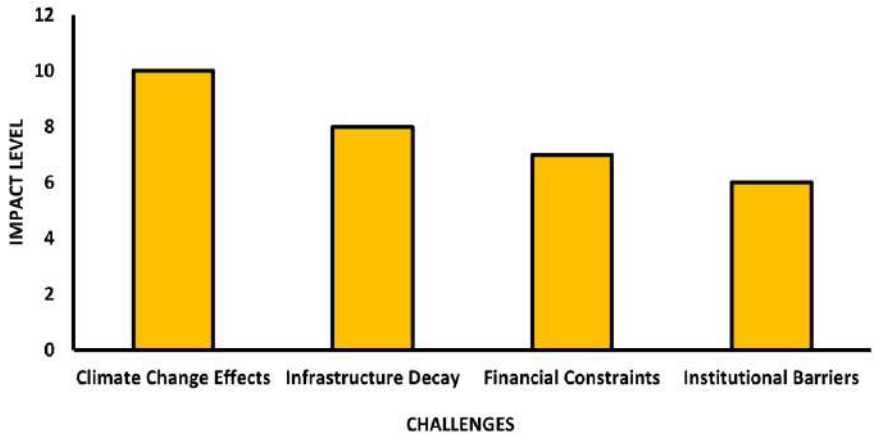

Fig 1: Key Challenges Facing Hydraulic Engineering in Sri Lanka (Source: Adapted from [5][8])

Apart from this, real-time hydrological surveillance, coupled with highly advanced warning systems, is likewise being established as an efficient tool for flood-risk monitoring. [13] record that flood-prone areas such as Colombo and Gampaha have started adopting real-time surveillance systems that track river levels, rainfall, and flood forecasts. These systems provide helpful details that would enable local authorities to make informed decisions when faced with floods. Early warning systems enable timely discharges and the activation of emergency procedures, thereby alleviating the repercussions of flooding in affected areas. Their uptake, nevertheless, has been reduced by the presence of financial and institutional constraints, making it challenging for countless city governments to embrace such complex innovations.

2.3 Sustainable Drainage Systems and Stormwater Management

The management of stormwater has become a persistent problem in the urban environment, especially as urbanization increases and impervious surfaces, such as buildings, roads, and pavements, rise [8]. An example is in Colombo, where the current drainage system has been found insufficient to handle increased surface runoff during heavy rainfall [3], [8]. Traditional stormwater drainage systems, based on large, centralized systems, are proving inadequate for dealing with the increasing volume and intensity of urban runoff.

Sustainable Urban Drainage Systems (SuDS) have also been proposed as an alternative to mimic natural hydrological processes, including infiltration, evaporation, and storage,

to manage stormwater more sustainably [8], [14]. SuDS methods include permeable pavements, green roofs, and rainwater collection systems that all reduce runoff volume, increase groundwater seepage, and lower flood risks in urban areas [14].

Although these are the benefits, SuDS have not gained much adoption in Sri Lanka. Some typical obstacles include regulatory loopholes, institutional fragmentation, and the lack of public awareness of the long-term benefits of sustainable drainage [8]. According to Ranasinghe and Ratnayake [8], government agencies, urban planners, and the population should be more collaborative in implementation. Moreover, they require further investigation to assess the functionality of SuDS in Sri Lanka's climate and hydrological conditions, as they could pose difficulties for their large-scale use [5], [8], [13].

3. RESULTS AND DISCUSSION

3.1 Climate Change Impacts on Hydraulic Systems

Climate change is the most significant challenge to the water infrastructure in Sri Lanka. Changing rainfall patterns, temperature rise, sea-level rise, and increasingly extreme weather events already affect the reliability, efficiency, and safety of reservoirs, canals, pipelines, and flood management infrastructures [5]. The Second National Communication Report to the UNFCCC (2012) indicates that Sri Lanka is extremely vulnerable to droughts and floods, often experiencing them in succession, thereby imposing serious obstacles to the sustainable management of the country's water resources. Extreme rainfall events are becoming more frequent. According to the Department of Meteorology, Sri Lanka (2021), the frequency of days with 100 mm or more rainfall shows a general increase of more than 30% in the 1980 decadal period. This overwhelms the existing urban drainage systems, particularly in the districts of Colombo, Gampaha, and Kandy, causing urban flash floods [13].

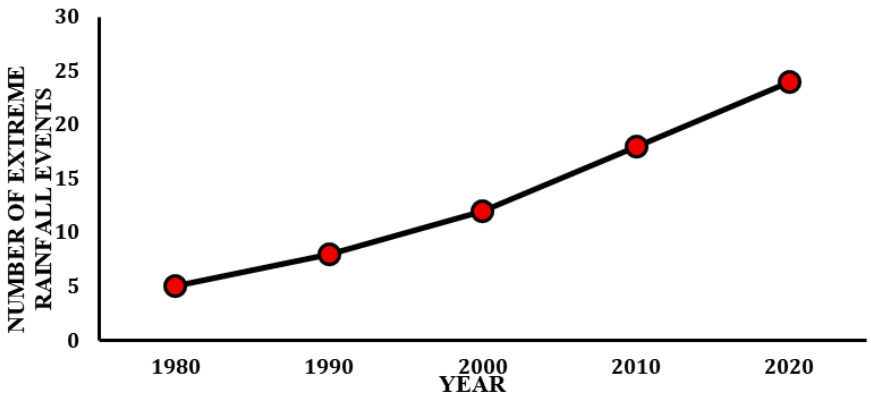

Fig 2: Increase in Extreme Rainfall Events

Reservoirs such as Victoria and Randenigala are designed based on observed historical rainfall patterns. Increases in rainfall intensities of already extreme events can increase the risk of overtopping the reservoirs and dam safety issues in case spillway designs are exceeded [6]. Storage capacity reduction may be faster than life assessments would indicate due to increasing sediment inflow rates during more frequent storms.

Extended Drought Periods. During the 2016-2017 drought, major reservoirs such as the Senanayake Samudraya were below 25% of their storage capacity, curtailing irrigation and creating drinking water shortages [4]. The unpredictability of seasonal water release from reservoirs heightens the risk to Sri Lanka's agriculture sector.

3.2 Urbanization Pressures on Hydraulic Systems

Urbanization in Sri Lanka has been increasing rapidly, projecting a linear urban expansion in and around the cities of Colombo, Gampaha, Kandy and Galle. The urban population has risen from 18%-30% of the total population from 1980–2020 [17]. Hence, such rapid urbanization, if not well-planned, can exert significant pressure on prevailing hydraulic systems (i.e., stormwater drainage and flood canals, pipelines and even the reservoir catchment). For this reason, such urban sprawl exerts more pressure on natural infiltration, surface runoff and interferes with the natural hydro-geological cycle to intensify the issues related to both the flood concentration and water shortage [8].

The removal of natural vegetation and replacement with impermeable bid surfaces such as asphalt and concrete means that rainwater can rapidly accumulate during a storm event. Research on Colombo has revealed that runoff coefficients have doubled in 30 years [5]. Urban flooding events, such as those experienced in Wellampitiya, Kolonnawa, and parts of Battaramulla during the 2016 floods, highlight the inadequacy of the current stormwater management infrastructure. The hydraulic capacity of the system is seriously reduced by illegal construction along canal reservations and flood retention areas. About 30% of the Colombo canal network is encroached upon by unauthorized structures [3]. Encroachments not only impede water flow but also hinder future expansion and maintenance activities, increasing cities' overall vulnerability to floods. Urban runoff carries pollutants—oils, heavy metals, and trash—into drainage networks and canals, leading to blockages, degraded water quality, and public health impacts during floods. Waste accumulating in canals such as Dehiwala and Wellawatte reduces the drainage efficiency by 15–20% each year [14]. MCUDP is a good example of how urban flood risk can be reduced by combining both engineering and planning solutions. Since its implementation, there has been a significant decrease in the frequency of flooding in high-risk areas of Colombo (World Bank, 2020).

The key successes include the Development of St. Sebastian's South Retention Lake, Micro-tunnelling stormwater drains beneath Colombo Fort and improved early warning systems and flood evacuation plans. The initiatives set examples for other similar cities, such as Kandy, Kurunegala & Galle.

Table 2: Comparison of Flood-Prone Areas Before and After (Source: MCUDP, 2021)

Area	**Major Flooding Incidents (Annual Average 2005–2010)**	**Major Flooding Incidents (Annual Average 2016–2021)**
Colombo Fort	5	2
Maradana	6	2
Pettah	7	2

3.3 Water Scarcity and Management Challenges

Whereas the water issue is traditionally viewed as an intensely agrarian problem, local and seasonal water shortage has emerged as a major issue of concern, especially in the Dry Zone, or the north-central, eastern, and southern areas of Sri Lanka, and even in large cities [4], [14], [3]. Increased inequity between water supply and demand is mainly caused by climatic variability, unsustainable extraction and exploitation of groundwater, ageing and poorly maintained water infrastructure, and uneven distribution of water in the regions [5], [11], [3]. The droughts of long duration, like the severe drought of 20162017, highlighted the frailty of the large reservoir systems, including Senanayake Samudraya, Parakrama Samudraya, and Maduru Oya that plummeted to under the crisis storage mark and were forced to accept emergency rationing of their irrigation as well as domestic water resource [4], [6]. Such interferences not only interrupted Maha and Yala production cycles, but also brought major challenges to food security, agricultural livelihoods, and the stability of the national economy [4], [2].

With the increasing population pressure and the industrial demand, the same challenges are experienced in the urban areas. An example is Colombo, which needs more than 700 million liters of water per day, but the losses of the water supply are at 30-35 percent of this quantity, which includes leakages, illegal connections, and ineffective management practices [7]. Intermittent water cuts have a direct effect on the industrial performance and quality of life in cities during prolonged dry seasons [3], [7]. In rural areas, where groundwater is mainly drilled unregulated through tube wells, especially in Anuradhapura and Polonnaruwa, tube well installations have increased the pace at which ground water is being depleted that could lead to the collapse of agricultural systems and rural water supply schemes [9]. To this, the decentralized water management efforts have proved to be quite successful. The Lanka Rainwater Harvesting Forum (LRWHF) has been encouraging rainwater harvesting technologies in schools, hospitals and dry-zone communities since the late 1990s and can serve as a reliable source of water during drought situations [14]. Such programs underscore the huge potential of cost-effective and community-based, and environmentally adaptive technologies in developing drought resilience and facilitating sustainable water management in Sri Lanka [14], [3].

3.4 Ageing Infrastructure Challenges

Much of the hydraulic infrastructure in Sri Lanka, such as reservoirs, canals, and transmission pipelines, is of colonial origin (19th -20th centuries) and other large-scale development projects, such as the Accelerated Mahaweli Development Programme of the 1970s and 1980s [12], [2]. Most of these systems which were initially the basis of agricultural and household supply of water have become old and have decreased performance and structural stability. The compounding forces of time, poor maintenance, and mounting climatic pressure have resulted in the deterioration of efficiency and the escalating safety risks on major aspects of the water system [5], [6]. Older and mid-20th-century reservoirs like Tissa Wewa and Parakrama Samudraya are currently experiencing massive seepage loss through eroded embankments, reduced storage capacity due to deposition of sediments and structural degradation in the form of fractured sluice gates and weaken sluice ways [6]. A recent national audit of reservoirs indicated that almost a quarter of these facilities have been rated as being of a high risk and this is mostly because of the lack of maintenance, and the operation systems are outdated [6], [9].

The same happens with water conveyance systems. Open-earth canals often emphasize small irrigation systems, lose up to 40per cent of their conveyance through seepage and evaporation, and as a result, most of the water never reaches farmlands in the dry zone [9]. These inefficiencies still worsen the situation of water shortage and undermine agricultural output, unless the canals are lined or operations controlled via real-time flow management [11], [6]. Ageing cast-iron water distribution pipelines in urban centers such as Colombo, Kandy and Galle often experience leakages and bursts leading to high non-revenue water (NRW), service disruption during peak and risks of contamination during floods [7]. The Ambatale Water Treatment Plant, which is one of the major facilities providing Colombo Metropolitan Region and regularly serving the growing urban population, also needs regular upgrades and retrofitting to withstand changing climatic and hydrological conditions and supply the population with clean water [3], [7].

3.5 Coastal Erosion and Sea Level Rise

Sri Lanka, as an island country, is especially prone to seaside dangers consisting of disintegration, tornadoes climb together with sea-level rise. About 24% of Sri Lanka's population lives within 10 kilometers of the coast as well, and over 70% of the tourist industry is coastal dependent [10]. The Coastal Erosion Management Plan of Sri Lanka (2010) determined sea-level increase and enhanced tornado strength as important dangers to seaside hydraulic frameworks consisting of breakwaters, sea walls surfaces, floodgates, as well as seaside supply of water systems. Studies suggest that seaside disintegration prices in particular locations such as Moratuwa, Kalutara, as well as Mullaitivu have sped up from 0.2- 0. 3 meters annually traditionally to 0. 5 - 0. 7 meters each year in the previous years [10]. This intimidates not just the suburbs but also crucial facilities like ports (Colombo, Hambantota) as well as seaside railway lines.

Rising sea levels trigger saltwater to invade inland right into seaside aquifers. In locations like Kalpitiya, along with Puttalam, salinization has actually made groundwater unsuitable for alcohol consumption and also watering [4]. This minimizes freshwater accessibility for seaside neighborhoods and also presents severe, long-lasting durability threats. Traditional hard-engineered defenses, such as groins and seawalls, are often insufficient under new high-energy wave conditions. Failures of these frameworks cause raised susceptibility of coastlines and also nearby inland water systems, consisting of rivers as well as lagoons [5]. The Marawila Coastal Protection Project (2015- 2018) incorporated overseas breakwaters, synthetic coastline support, along with mangrove repair. Consequently, seaside disintegration prices went down considerably while tourists as well as fisheries recouped [18]. This success shows the possibility of crossbreed, ecosystem-friendly remedies in the Sri Lankan context.

3.6 Policy and Governance Gaps

Managing Sri Lanka's hydraulic schemes effectively requires not only engineering capabilities but also robust institutional structures and policy coordination. Many water-related efforts are poorly executed in part due to fragmented governance, overlapping responsibilities and mandates, and weak implementation protocols [11].

In the absence of systemic improvements in the way the country is governed, even technically sound projects can fail or underperform. These institutes often do not coordinate well with each other, which causes duplication of effort or work being

overlooked [5]. For example, projects on flood management can be considered exclusively, without any need to consider interactions with urban planning or environmental impact assessment. Although Sri Lanka has certain laws and regulations, such as the National Water Policy (drafted in 2000) and the Coast Conservation Act (1981), enforcement of these laws is still lacklustre as political pressure coupled with a lack of labour and funding prohibit sufficient implementation [4]. Illegal construction along flood retention areas and unregulated groundwater extraction persists, notwithstanding formal bans. Hydrological and meteorological data are not shared in real-time among agencies. Some reservoir operators still depend on obsolete manual measurement techniques, hindering predictive flood and drought management ability [10].

3.7 Engineering and Policy Solutions for the Future

To respond to the complex disasters plaguing the hydraulic infrastructure in Sri Lanka, the country needs to shift its approach to maintenance as a reactionary measure and lack of coordination with technology-based, integrated, and comprehensive water governance system [11]. A combination of technologies of the latest engineering advances, flexible policy frameworks, institutional coordination, and community-based engagement will determine the sustainability of the hydraulic network of the country. One of the major changes is the implementation of Internet of things (IoT) based sensor networks which monitor and control real-time huge reservoirs, irrigation canals and drainage pathways [13]. The constant check of water levels, sediment load, rainfalls, and rate of discharges would allow the active control of releases, better predictions of droughts and floods, and allow sharing the data on a transparent basis among the water management bodies. The analysis of these systems with Geographic Information Systems (GIS) and remote sensing tools might also facilitate the accuracy of decision-making and spatial water balance control. At the same time, Artificial Intelligence (AI) and Machine Learning (ML)-based predictive maintenance models have the potential to transform the asset management process, predicting structural failures, leakages, or declines in their efficiency as the assets age, accumulate stress, or deteriorate because of climate changes. Pilot applications to key infrastructure in the Victoria Dam and Parakrama Samudraya and the flood tunnel-network in Colombo can be used to show the scalability of predictive analytics in maximizing long-term asset resiliency. In line with technological innovations, the modular water treatment and recycling facilities provide a strategic avenue towards the mitigation of the increasing pressure on centralized water treatment units and city water systems [7]. The deployment of the decentralized modular units in peri-urban zones, industrial zones, and coastal zones would improve the flexibility of operations, minimize the transmission losses of water, and increase water reuse in non-drinking purposes like landscaping and industrial cooling. Placing rainwater harvesting, eco-engineered wetlands, and green infrastructure into urban planning (e.g., bioswales, permeable pavements, and retention ponds) can be of great benefit to groundwater recharge and alleviate urban flooding [14], [8], [13]. Moreover, the water policy framework in Sri Lanka needs to emphasize on the concept of climate-adaptive governance where there is a greater coordination of agencies such as the NWSDB, Irrigation Department, and Mahaweli Authority in order to formulate unified basin-scale management options [11], [3]. It is also necessary to maintain these technological interventions through capacity building, community involvement and programs about awareness to the population. By working together through this, namely, the connection of innovation, institutional reform, and social

participation, Sri Lanka will be able to create a resilient, efficient, and sustainable water sector that will be able to resist future climatic and developmental pressures [11], [7], [13].

4. CONCLUSION

Sri Lanka's hydraulic systems-- a tradition of old design quality integrated with contemporary treatments-- create the foundation of the country's farming water system, power generation together with metropolitan flooding monitoring. Nonetheless, expanding stress from environmental adjustment, fast urbanization, ageing facilities, water deficiency, along with administrative weak points threatens the lasting sustainability as well as durability of these systems.

The detailed analysis in this report highlights the following critical points:

1.Climate variability, defined by even more extreme rains along with extended dry spells, is stressing tank monitoring, flooding support, plus watering preparation [5]

2.Unplanned urbanization has enhanced flooding threats and weakened canal systems, combined with placing extra stress on the piped supply of water systems [8]

3.Water scarcity is arising in both backwoods plus city locations, driven by increased demand for inadequate facilities and excessive groundwater usage [7]

4.Coastal areas encounter sped up disintegration and also salinity breach because of sea-level surge, jeopardizing areas, communities, and hydraulic facilities [10]

5.Fragmented governance and outdated policies prevent work with the hydro sources administration, coupled with facilities durability structure

Even with these difficulties, Sri Lanka has actually shown capability for technology, as evidenced by the Mahaweli Development Programme, the Metro Colombo Urban Development Project, together with an effective seaside crossbreed design service [3]. It appears that a future-focused approach incorporated with a climate-resilient strategy is important for safeguarding Sri Lanka's hydraulic heritage as well as conference arising socio-economic and ecological needs.

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Rethinking Sri Lanka's Hydraulic Engineering for Climate-Resilient Development: Bridging Historical Systems with Smart Technologies

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Abstract— Sri Lanka's hydraulic civilization, shaped by ancient systems like the tank cascade systems and large reservoirs, has supported the country's water management and agriculture for centuries. However, climate change, urbanization, and ageing infrastructure now challenge the resilience and efficiency of these systems. This paper reviews the current state of Sri Lanka's hydraulic infrastructure, including reservoirs, irrigation schemes, and urban water systems, based on case studies such as the Mahaweli Development Programme, the Bellankadawala cascade system, and the Kelani River flood mitigation project. International best practices in Singapore, Japan, and the Netherlands are examined to determine innovations that can be adapted. Findings highlight recurring issues such as sedimentation, evaporation losses, pipeline leakage exceeding 30%, and limited application of digital solutions like GIS-based monitoring and predictive flow models. While projects in early stages have shown feasibility, large-scale adoption is low due to policy limitations, infrastructure gaps, and delays in funding. The study finds that integrating digital technologies with Sri Lanka's existing systems has the potential to increase performance, reliability, and climate resilience. When complemented by real-time data, automated control, and predictive analytics, traditional systems offer a pathway to sustainable water management. Suggestions vary from scaling up smart irrigation projects to enhancing reservoir monitoring systems and improving urban pipeline maintenance, in addition to addressing governance concerns. Policy, technological, and community-level intervention coordination needs to be reinforced for the future water security of Sri Lanka.

Keywords— Climate Adaptation, Hydraulic Engineering, Irrigation Networks, Water Management

1. INTRODUCTION

Sri Lanka's hydraulic system sector is central to the development of its national infrastructure, economic stability, and resilience to disasters. Efficient water resource management is important to the country's agriculture, urban and rural water supply, and flood mitigation efforts. Although Sri Lanka has been widely acknowledged as one of the world's most advanced hydraulic civilizations in the ancient world, with a history of more than two millennia of irrigation and water management systems, modern challenges demand modern hydraulic engineering solutions. This report critically evaluates Sri Lanka's hydraulic infrastructure, its challenges, and engineering solutions, considering case studies of the Mahaweli Development Program (MDP), Kelani River Flood Mitigation Project, and Victoria Dam.

While Sri Lanka was traditionally renowned for its exceptional hydraulic systems, other nations such as the Netherlands, China, and Singapore have surpassed it. For Sri Lanka to improve the current position it holds in the field, it must modernize its approach. Sri Lanka has long been known for its hydraulic and irrigation systems, a legacy dating back more than 2000 years, and its ancient wewa systems, massive reservoirs built for water storage and water management, were built under the reigns of kings such as Parakramabahu I and Dhatusena, showcasing the kind of vision only a few possess regarding water management and distribution, especially at that time. These hydraulic structures, alongside the advanced tank cascade systems, transformed the island's arid regions into thriving agricultural landscapes. Thus, it sets a global precedent for sustainable water management. Yet today, with rapid technological transformation in many areas, including hydraulic engineering, Sri Lanka must ensure that it does not simply bask in past success but actively works to improve its water facilities to meet today's needs.

Efficient hydraulic systems are crucial to the stability of the nation, playing a direct role in food security, urban resilience, and energy production. Agriculture remains a cornerstone of Sri Lanka's economy, with nearly 31% of the population actively engaging in irrigation-farmed agriculture and a staggering 18% of the nation's GDP relying on agriculture. Also, hydropower supplies a considerable portion of the country's electricity, highlighting the significance of well-maintained reservoirs and sustainable water management. However, unavoidable conditions such as urban flooding in Colombo and increasing strain on existing irrigation networks emphasize the urgent need for modernization of approaches and climate-proofing. While Sri Lanka's historic approaches towards water management were revolutionary at the time, other countries have since refined and expanded upon these principles, offering models that Sri Lanka can implement. Sri Lanka can strengthen its hydraulic heritage and water management approaches by integrating sustainable strategies, predictive hydrological models, new engineering methods, and artificial-intelligence-driven irrigation networks.

2. METHODOLOGY

2.1 Study Design

This paper presents a structured review of Sri Lanka's hydraulic engineering systems, with particular emphasis on climate resilience, performance challenges, and the feasibility of integrating smart technologies. The study does not involve primary data collection; instead, it draws upon data from selected literature, engineering case studies, and international benchmarks to evaluate both historical and contemporary approaches to water management.

2.2 Reference Selection Criteria

A total of twenty-five published sources, spanning the years 1999 to 2025, were examined for this review. These sources include technical evaluations, policy documents, hydrological studies, and accounts of global engineering practices. References were selected based on their relevance to key thematic areas, namely Sri Lanka's reservoir and irrigation systems, urban and rural water distribution networks, sedimentation and flood mitigation strategies, the impacts of climate change on hydraulic infrastructure, and international models of smart water management and predictive control.

The literature was identified through targeted research conducted on Google Scholar, institutional databases, and official government websites. Priority was given to publications with a high citation count, materials from authoritative sources, and studies offering either significant technical depth or strong practical applicability to Sri Lanka's hydraulic context.

2.3 Case Study Integration

The review integrates case studies from both local and international contexts to provide comparative insights and evidence-based analysis. Local examples include the Mahaweli Development Program, the Victoria Reservoir, the Bellankadawala tank cascade system, the Kelani River flood mitigation project, as well as case studies addressing urban water supply challenges in Colombo and rural water access issues in Anuradhapura and Monaragala. These are complemented by international benchmarks selected for their relevance and transferability to the Sri Lankan context. The global examples include Singapore's Smart Water Grid, Japan's G-Cans flood tunnels, the Netherlands' Delta Works and Maeslant Barrier, and China's Xiaolangdi Dam sediment flushing system. Together, these case studies enable comparative assessment, help identify performance gaps, and inform the development of feasible interventions for the modernization of Sri Lanka's hydraulic systems.

2.4 Structuring

The paper is organized around several key engineering themes derived from the selected literature. These include the historical evolution of hydraulic systems, the dynamics of fluid flow in irrigation and flood control, sediment transport and river morphology, hydrodynamic challenges in coastal and inland water systems, the performance of reservoirs and canals, urban and rural water distribution, the impacts of climate change and corresponding adaptive strategies, and finally, the integration of global best practices and smart technologies. Each theme is supported by technical findings and contextual analysis, with references to specific systems and interventions that collectively form the foundation for the study's recommendations.

3. LITERATURE REVIEW

3.1 History & Evolution of Hydraulic Systems in Sri Lanka

Sri Lanka's hydraulic engineering has deep roots in the Anuradhapura and Polonnaruwa dynasties, as their rulers, like King Vasabha and King Parakramabahu I, led reservoir network and irrigation canal construction that impacted agricultural output. During the Anuradhapura era, the construction of enormous tank systems, such as Abhaya Wewa and Minneriya Tank, introduced highly efficient water storage and flood mitigation methods, enabling farming year-round. By the Polonnaruwa period, hydraulic structures became more sophisticated, with multi-purpose reservoirs serving irrigation and urban water supply. Parakrama Samudraya, arguably the finest achievement of its time in engineering, demonstrated early principles of integrated water resource management, ideas that are only now being developed by modern models of sustainability. In comparison with global hydraulic achievements, Sri Lanka's ancient water systems rival ancient Mesopotamian irrigation works and Roman aqueducts. Although modern nations use AI-based water grids and automated flood barriers, ancient Sri Lanka reveals that engineering skill has been at play for centuries before the rest of the world.

3.2 Fundamental Principles in Hydraulic Engineering

Fluid dynamics control the flow of water in hydraulic networks, determining the efficiency of irrigation, flood control, and water distribution. Viscosity in irrigation systems in Sri Lanka directly influences flow resistance, how quickly water will flow through systems of open channels [1]. Higher viscosity encourages more resistance and reduced flow rates, while lower viscosity offers greater mobility, particularly within gravity-fed irrigation channels. Sri Lanka's traditional tank cascade systems, including the Bellankadawala cascade system, rely on elevation differences to facilitate water movement naturally. These interconnected tanks store and distribute water efficiently, supporting agriculture and local ecosystems without mechanical intervention. The Bellankadawala cascade system plays a critical role in maintaining the hydro-environmental balance, demonstrating the adaptability of Sri Lanka's ancient hydraulic engineering to seasonal changes [2].

Water flow in hydraulic systems is classified as open-channel or closed-channel flow, each having distinct characteristics. Open-channel flow, found in Sri Lanka's reservoir and canal networks, depends on gravity flow, which supports large-scale irrigation projects such as the Mahaweli Development Program [3]. In comparison, closed-channel flow, common in urban drainage and potable water supply, requires pressure regulation devices to facilitate efficient distribution across urban areas, particularly for Colombo's expanding pipeline network. Flow behaviour is also distinguished between laminar and turbulent flow, both of which have their specific difficulties in hydraulic engineering applications. Laminar flow, with its smooth and predictable movement, is best suited for controlled irrigation systems to supply a steady and uniform water supply. Conversely, turbulent flow increases erosion and sediment transport, particularly in Sri Lanka's flood-prone Kelani River Basin, where rapid flow variations increase flood risk and sediment relocation [4].

3.3 Sediment Transportation & River Morphology

Sedimentation impacts Sri Lanka's hydraulic structures by reducing reservoir capacity and altering river dynamics. In Polgolla and Rantambe, soil accumulation restricts storage, affecting water control and requiring dredging [5]. Similarly, urbanization and deforestation in the Kelani River Basin catalyze erosion, worsening sedimentation, and flood risks [4]. Figure 1 illustrates this issue in China's Lower Yellow River at Huayankou, where sedimentation has reduced the flood conveyance capacity, mirroring Sri Lanka's issue in Kelani Basin. Globally, China's Xiaolangdi Dam uses controlled flood waves to flush sediments, restoring stability to the riverbed [6]. Figure 1 depicts this strategy, which Sri Lanka could implement to achieve long-term reservoir efficiency and flood resilience.

3.4 Hydrodynamic Concepts for Coastal and Inland Water Systems

Sri Lanka's coastal structures are vulnerable to increasing storm surges, particularly in Colombo and Kalutara, where wave action hastens erosion and flood defences are threatened [7]. Inland, reservoir hydrodynamics is crucial in energy generation, with Victoria Reservoir showing thermal stratification, a phenomenon where water forms separate temperature layers, affecting circulation, oxygen supply, and the efficiency of hydropower. Meanwhile, flash floods and seasonal shortages are aggravated by climate-driven changes, in line with global patterns of disruption of the hydrological cycle.

Strengthening predictive modelling and flood management solutions can support Sri Lanka's resilience against hydrodynamic challenges, ensuring long-term water resource sustainability.

3.5 Reservoirs, Canals & Irrigation Networks

Sri Lanka's hydraulic network is most important for water storage, irrigation, and energy generation, where reservoirs such as Victoria, Randenigala, and Parakrama Samudraya are some of the most significant ones. Victoria Reservoir, constructed in 1985, is a primary hydropower source, while Randenigala is utilized for regulating Mahaweli River flow to support agriculture [3]. Parakrama Samudraya, the largest of the ancient reservoirs for irrigation purposes, represents the brilliance of ancient engineering applications in handling water resources. As King Parakramabahu, I have famously quoted, "Let not drop water go to the sea without being made use by mankind." The Mahaweli Development Programme (MDP), Sri Lanka's largest irrigation project, transforms agriculture and power production, connecting several irrigation systems such as Systems B, C, and D (Sri Lanka Ministry of Irrigation, 2025). Nevertheless, modern irrigation faces issues in water supply, including evaporation losses, ageing canal structures, and wasteful supply systems [8].

Comparing traditional tank cascade systems with modern irrigation systems results in differences in sustainability and efficiency. Although the traditional tank systems ensured groundwater recharge and flood protection, modern infrastructure focuses on rapid water delivery but struggles with long-term ecological sustainability [7]. Future projects must incorporate sustainable water management principles, balancing efficiency and environmental preservation.

Fig. 1: Man-made flood generation in the Yellow River at Xiaolangdi, China. (Source: Liu, et al. [1])

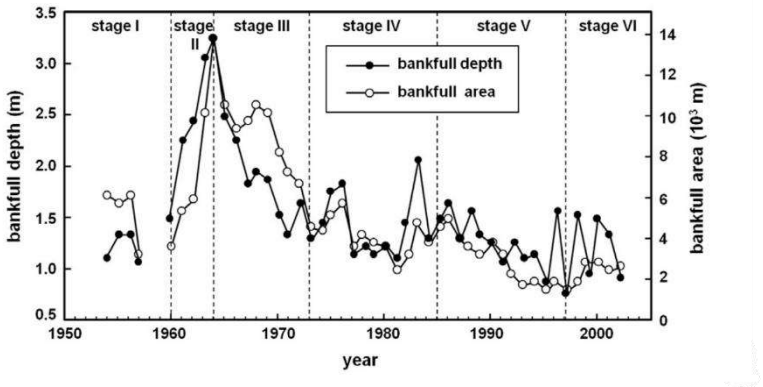


Fig. 2: Evolution of depth and cross-sectional area of the Lower Yellow River at Huayankou Station, China. (Source: Liu, et al. [1])

3.6 Urban & Rural Water Supply

Colombo's ageing plumbing structures face significant challenges, with leakage rates as high as 49% in areas such as Borella and Pettah, where pumping stations are strained with outdated demand patterns [4]. Seasonal shortages in rural parts of Anuradhapura and Puttalam limit the availability of clean drinking water, forcing reliance on protected wells and rainwater harvesting. Government policies, including pipeline expansions and desalination projects, such as the Thalaiyadi seawater desalination plant, were initiated to increase water security. Improving filtration systems and sustainable groundwater management is essential for durability and long-term performance.

3.7 Impact of Climate Change on Water Management

Changing rainfall patterns are a disturbance to Sri Lanka's water management system, with intensifying droughts in the North Central Province and the Maduru Oya Basin affecting reservoir storage and the reliability of irrigation. Subsequently, flood-prone zones like Colombo and Gampaha have runoff increases, strain on infrastructure, and increased threat from disasters. To counter these impacts, initiatives such as rainwater harvesting in Kilinochchi and Monaragala offer sustainable water solutions, while adaptive flood control measures mimic international strategies in climate-resilient planning of infrastructure.

4. GLOBAL BEST PRACTICES

Sri Lanka could learn from other nations that have mastered water management through advanced engineering. The Netherlands' Delta Works and Maeslant Barrier are prime examples, with massive coastal defences called "dikes" designed to block storm surges and regulate water inflow in vulnerable areas [9]. On the other hand, Sri Lanka's coastal flood protections remain scattered and reliant on natural barriers, so a more comprehensive approach to durable resistance is necessary. Meanwhile, Singapore's Smart Water Grid enhances the efficiency of water distribution through AI-powered

monitoring and predictive analytics to support leak detection and supply maximization [10]. Urban water supply infrastructure in Sri Lankan cities, such as Colombo, can make use of sensor-based leak detection and predictive maintenance to prevent water losses. Also, Japan has explored strategies for flood resilience in the form of automated flood tunnels like the Tokyo G-Cans project, effectively diverting excess water. Although Sri Lanka does not face seismic risks, the adoption of flood diversion strategies from Japan's urban drainage systems could help reduce urban flooding in Colombo and Gampaha. The addition of global best practices into Sri Lanka's water infrastructure could strengthen long-term resilience and improve hydraulic efficiency.

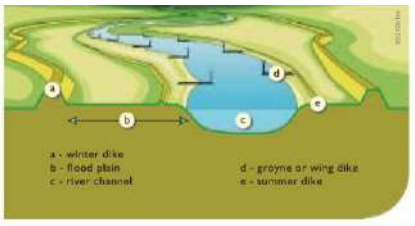


Fig. 3: Two-tier dike structures and groins for flood protection along the rivers in the Netherlands

Sri Lanka's decentralized reservoir and tank cascade-based water storage system offers local water security with less need to be dependent on large-scale urban grids. This approach enhances rural resilience but without predictive control and real-time monitoring, contrasted with Singapore's artificial intelligence-based water grid that optimizes distribution and leakage prevention [11]. Reactivating Sri Lanka's traditional tank systems through sensor-based monitoring would increase water distribution efficiency, offering optimal use and conservation. AI models such as predictive water balance models used in intelligent irrigation systems across the globe could be utilized with Sri Lanka's tank systems, offering improved storage regulation and fewer losses [10]. Both sensor-managed irrigation and predictive modelling are feasible yet challenging alternatives in Sri Lanka. While machine learning-based flood forecasting has been evaluated in the Nilwala River Basin, global adoption is stunted by inadequate funding and infrastructure [12]. The addition of sensor-managed irrigation, such as artificial intelligence to precision agriculture, may balance seasonal shortfalls but hinges on policy support and investment. Integrating the best global practices into Sri Lanka's hydraulic system can promote efficiency, sustainability, and climate resilience, combining historical wisdom with modern technology.

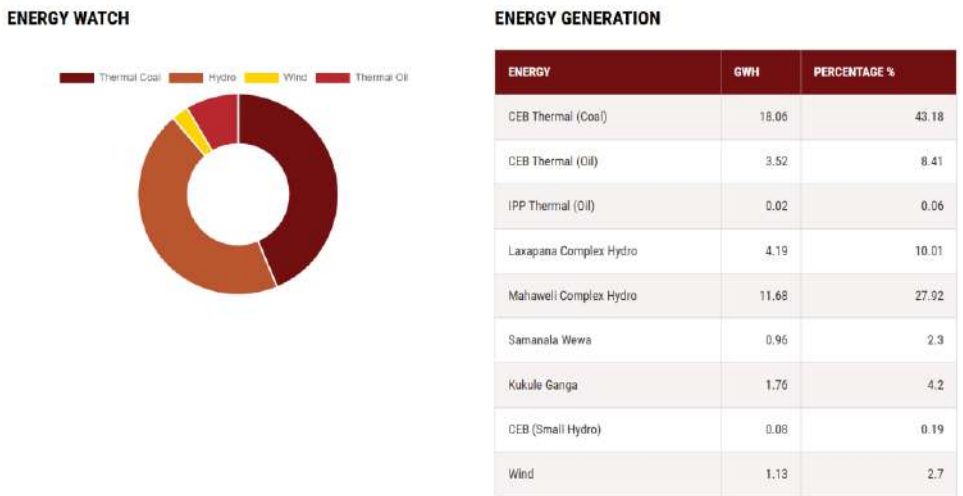
Despite Sri Lanka's strong hydraulic past, modern water management faces technological, predictive, and policy-related gaps that hinder efficiency and resilience. One of the most pressing constraints is the lack of hydrological simulations to optimize irrigation networks. While global models take advantage of real-time flow predictions, Sri Lankan irrigation planning remains rooted in static historical data, leading to inefficient water allocation [13]. Additionally, the lack of automated sediment flushing in reservoirs also accelerates capacity loss, reducing long-term efficiency. Efficiency research of sediment traps highlights the importance of hydraulic flushing mechanisms, but adoption remains limited [14]. AI-powered irrigation presents an opportunity to enhance predictive water distribution, but feasibility concerns, such as data availability and infrastructure readiness, hinder adoption [15].

Sri Lanka's flood forecasting models remain reactive rather than preventive, relying on post-disaster remediation efforts and not on machine-learning-based risk assessments. Experimental flood forecast models have been implemented in the Nilwala River Basin, but mass-scale adoption is constrained by resources as well as expertise [12]. In contrast, other countries like Japan and the Netherlands use sensor-driven flood monitoring, reducing disaster impact through early response systems [13]. Economic constraints also limit hydraulic research and modernization efforts. Inconsistent policy enforcement generates disconnected infrastructure development, while financial shortfalls prevent large-scale use [8]. Addressing these gaps requires integrated technological advancements, predictive models, and better policies to ensure Sri Lanka's hydraulic systems remain sustainable and resilient.

5. CURRENT STATE ANALYSIS

5.1 Sri Lanka's Existing Hydraulic Infrastructure

Sri Lanka's reservoirs are of much importance for hydropower, irrigation, and water storage, yet efficiency is hindered. Evaporation rates in the country's major reservoirs, including Victoria and Randenigala, reduce storage capacity substantially, particularly during dry seasons, affecting the availability of water [3]. Sedimentation also restricts reservoir efficiency, requiring dredging and automated flushing systems, which have not yet been widely implemented [16]. In addition, Samanalawewa Reservoir, a 120 MW hydropower plant, has suffered from continuous leakage (~1,800 liters per second) since its construction, limiting energy generation despite sealing with a grout curtain [2] Given that hydropower supplies nearly 40% of Sri Lanka's electricity [16], and 31% of the population depends on irrigation-fed agriculture, water resource management directly impacts both energy and food security [17]. Additionally, agriculture contributes approximately 18% of the nation's GDP, highlighting the vital role of reservoirs.



ENERGY	GWH	PERCENTAGE %
CEB Thermal (Coal)	18.06	43.18
CEB Thermal (Oil)	3.52	8.41
IPP Thermal (Oil)	0.02	0.06
Laxapana Complex Hydro	4.19	10.01
Mahaweli Complex Hydro	11.68	27.92
Samanala Wewa	0.96	2.3
Kukule Ganga	1.76	4.2
CEB (Small Hydro)	0.08	0.19
Wind	1.13	2.7

Fig. 4: Hydropower contribution from major Sri Lankan reservoirs (Source: https://ceb.lk/electricity-generated/en)

Sri Lanka's Mahaweli irrigation canal system, the largest canal-based network, supplies an agricultural water supply but is afflicted with flow regulation inefficiencies.

Comparatively, the Bellankadawala cascade system is part of Sri Lanka's traditional tank network, where interconnected irrigation tanks store and convey water efficiently. These systems regulate water availability by capturing rainwater and directing it through natural drainage mechanisms, supporting agriculture during dry seasons. The design of these cascades ensures optimal water distribution across paddy fields, demonstrating an adaptive approach to sustainable irrigation developed over centuries [2]. However, more recent canal systems lack precision flow monitoring, causing delays in irrigation and inconsistencies in distribution. Urban pipeline networks, particularly in Colombo, are challenged by old pipes and over 30% leakage in high-demand areas [18]. Population growth further pressures supply systems, making water shortage a more critical issue. While government rehabilitation projects improve distribution efficiency, funding limitations slow progress [9]. Enhancing the hydraulic infrastructure in Sri Lanka with the inclusion of automated sediment flushing, AI-powered leak detection, and improved flow monitoring could significantly transform long-term efficiency and resilience.

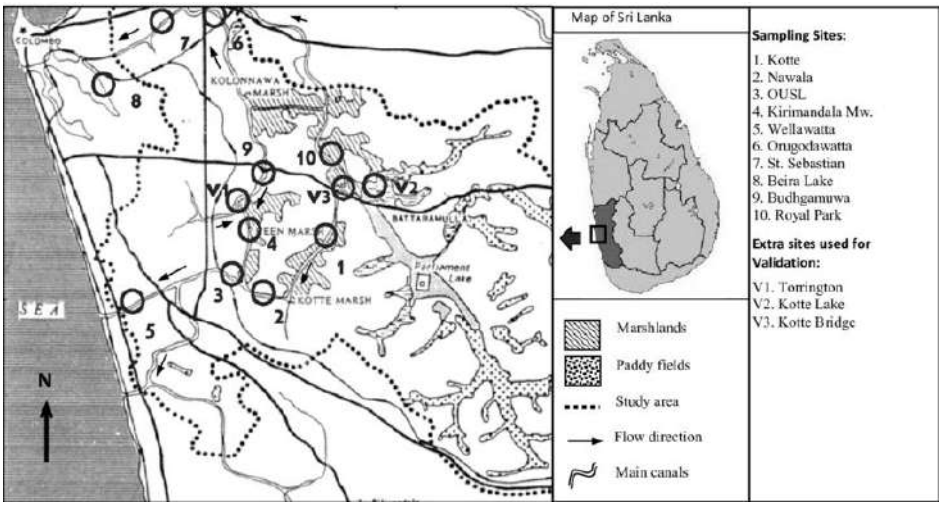


Fig. 5: Colombo-Sri Jayawardenapura Canal Network

5.2 Performance Evaluation & GIS Mapping

Sri Lanka's reservoirs face two major challenges: evaporation losses and sedimentation. Victoria Reservoir loses up to 15% of its storage annually due to evaporation, while Randenigala and Samanalawewa experience seasonal fluctuations impacting water availability [3]. Sedimentation rates vary, with Mahaweli reservoirs losing capacity at 0.5–1% per year, compared to global benchmarks of 0.2–0.5% [16]. Traditional tank systems like Bellankadawala have historically relied on natural filtration and buffer zones to manage sedimentation. Still, shifts in land use and irrigation practices have changed their long-term resilience [2]. Canal inefficiencies further affect water distribution and irrigation performance. Leakage rates in ageing canals exceed 25% in certain regions, particularly within the Mahaweli and Kirindi Oya systems, compared to international standards of <10% [8]. The lack of real-time flow monitoring leads to manual operation delays, reducing overall irrigation efficiency [19]. AI-driven

automated monitoring could enhance flow regulation and distribution, but high costs limit feasibility [20].

Sri Lanka's hydraulic network is vast, and Geographic Information System (GIS) mapping is needed to monitor water systems, identify inefficiencies, and guide better resource management. GIS is more than a technical tool; it visually represents how reservoirs, canals, and pipeline networks relate to each other, helping engineers and policymakers make educated decisions [21]. Reservoir management must account for climate-driven shifts in water availability. In the Basnagoda Reservoir, higher runoff coefficients lead to increased surface water storage, improving irrigation capacity but reducing groundwater recharge. Seasonal variability affects domestic water fulfilment, with availability rising slightly from 18% to 22% in Maha but more significantly from 19% to 33% in Yala. Due to flood vulnerability, the reservoir also serves as a retention basin, helping regulate excess water and minimize downstream risks [22], [23]. Sri Lanka's canal networks, particularly Mahaweli and Kirindi Oya, must be updated in determining sediment accumulation rates and flow disruptions [16]. Real-time GIS models would enhance maintenance schedules and streamline the processes of water distribution, minimizing blockages.

5.3 Urban & Rural Water Distribution Systems

Sri Lanka's water distribution network presents a stark contrast between urban centres and rural communities. In cities like Colombo, access to piped water is generally reliable but persistently strained because of ageing infrastructure and excessive leakages that continuously strain the network [19]. Urban consumers benefit from a regular supply and centralized water treatment, although delays in maintenance and clogged pumping stations can temporarily lower water pressure. Conversely, rural areas, specifically Anuradhapura, Puttalam, and Monaragala, are burdened with typical seasonal deficiencies due to groundwater depletion and irregular rainfall patterns [8]. Aquifer supplies in Anuradhapura have endured huge depletion, affecting both agriculture and domestic needs. Prevention measures against shortages include rainwater harvesting programs in Puttalam as an alternative water source for households [4]. Apart from access, water treatment needs drastically differ between urban and rural areas. Cities rely on advanced purification methods to supply clean drinking water, while villages have more basic filtering techniques, which pose higher public health risks.

TABLE I: Comparison between Urban & Rural Water Supply Efficiency

FACTOR	URBAN AREAS (Colombo/Kandy)	RURAL AREAS (Anuradhapura, Monaragala)
Water Source	Piped networks, reservoirs	Groundwater, rainwater harvesting
Treatment Methods	Centralized purification	Basic filtration, untreated water
Reliability	High, but occasional disruption	Seasonal shortages, inconsistent supply
Main Challenges	Aging infrastructure, leakage	Groundwater depletion, reliance on rainfall

Colombo's drainage system experiences issues of frequent overflows and blockages, especially in the Maradana and Pettah regions, where densely developed and poorly drained areas increase flood risks. The 2010 and 2016 floods were extremely severe, with roadways being underwater for hours, disrupting transport and commercial activities. Lack of maintenance and solid waste clogging of stormwater drains also cause diminished efficiency of flow. This leads to localized waterlogging at moderate rainfall. On the other hand, provincial irrigation schemes in Sri Lanka's dry regions are faced with water shortages rather than abundance, with mini-irrigation systems struggling to meet agricultural demands. Small tank-based irrigation has been the focal point of government rehabilitation efforts in Puttalam, Anuradhapura, and Kurunegala, where climate uncertainty has intensified drought conditions. The Smallholder Agribusiness and Resilience Project (SARP) aim to improve adaptive capacity by improving efficiency in water storage and supply to deliver greater resilience for rural farmers. While Colombo's drainage malfunctions are the result of urban expansion and infrastructure neglect, provincial irrigation constraints are due to water shortages based on climatic factors and inefficient irrigation techniques. Addressing both involves selective investment in the modernization of drainage systems and ecological irrigation.

5.4 Flood Management Strategies

Urban flood management in Sri Lanka relies on both natural and engineered measures yet increasing urbanization and climate uncertainty pose severe challenges. In Colombo, wetland ecosystems naturally buffer floods by absorbing excess rainwater and reducing surface runoff. However, encroachment and land filling have diminished their effectiveness, leading to higher flood risks [22]. Engineered systems, including rainwater drainage networks and diversion systems, attempt to minimize flooding, but blockages from waste accumulation and ageing infrastructure frequently result in localized waterlogging [23]. Flood mitigation policies led by the government focus on early warning systems and drainage modernization. The Kelani River Basin Flood Prediction System uses machine learning algorithms to predict increases in water level, improving emergency preparedness [5]. Additionally, city-wide drainage development, funded through international aid programs, has strengthened Colombo's flood endurance capabilities, though implementation delays remain a major concern. Climate change has made urban flooding more recurrent, and rainfall patterns have become less predictable and more erratic. Sri Lanka's Flood Response, compared to other South Asian cities, continues to be a work in progress and requires higher investment in infrastructure and nature-based solutions [24].

Sri Lanka makes use of diversion canals and embankments to manage river flooding, such as in Deduru Oya, where regular floods threaten agriculture and settlements. The Deduru Oya Flood Diversion Project redirects the excess water into storage reservoirs, reducing the risk of overflow [8]. Topography constraints preclude large-scale inter-basin diversions, making localized flood control measures such as reinforced embankments and controlled spillways necessary [4]. Flood protection along the coast is equally critical, especially in Trincomalee and Galle, where there is a higher threat from increased sea levels and storm surges. Galle's coastal flood barriers use wave energy dissipating structures, while Trincomalee's breakwaters protect port facilities and residential areas [21]. Despite these defences, Sri Lanka remains vulnerable to extreme weather, mandating continuous improvement [24]. Bangladesh provides a

positive global example for coastal flood management, with cyclone-resistant embankments and early warning systems protecting low-lying delta regions.

6. KEY LIMITATIONS, TECHNICAL CHALLENGES IN CURRENT SYSTEMS

Sri Lanka's reservoir and canal infrastructure are faced with critical maintenance challenges, particularly with ageing structures that have been strained by defaulted maintenance and failed rehabilitation programs. For example, the Rajangana Reservoir was once a high-capacity irrigation source but now struggles with sediment accumulation, reducing its efficiency. Similarly, the Deduru Oya Canal System, as a key irrigation conduit for agriculture, has experienced erosion and embankment failures, resulting in recurrent water losses. Despite repair works led by the government, funding delays and technical issues have left many critical water systems operating below optimal capacity [4]. Pipeline failures also worsen water supply challenges, particularly in cities beyond Colombo and Kandy. Excessive leakage rates in Jaffna and Ratnapura cause the aged pumping stations to strain to maintain pressure stability. The Jaffna Water Supply Development Project, aimed at modernizing pipeline infrastructure, has been stalled by the slow pace of implementation, leaving residents dependent on spasmodic supply [17]. Likewise, Ratnapura's ageing pipeline network, designed for lower population densities, today suffers from frequent bursts and inefficiencies, requiring urgent upgrades.

Delays in repair have significant economic consequences, with an estimated rehabilitation of Sri Lanka's water infrastructure needing over $500 million in staged investments, yet budget constraints continue to slow progress [6]. Comparatively, Pakistan's urban water systems face similar challenges, as Karachi's outdated pumping stations are unable to meet increasing demand, showcasing a shared regional struggle in water infrastructure modernization [25]. Sri Lanka's modernization of its water infrastructure sector has been hindered by funding shortages and inefficiencies, delaying critical renovations and upgrades. Despite budgets being allocated, several large projects remain stalled, including the Ratnapura Water Supply Expansion, which saw procurement delays and cost overruns, resulting in thousands having irregular and inconsistent access to clean water [17]. Similarly, the Deduru Oya Canal Rehabilitation to enhance irrigation efficiency has not progressed much due to budgetary constraints, worsening the loss of water in agricultural regions [22]. The Anuradhapura Water Distribution Upgrade, a project meant to increase piped supply for both urban and agricultural use, has also halted due to financial mismanagement and contractor disputes. These issues illustrate deep-rooted inefficiencies in financing water infrastructure. Regulatory enforcement gaps also contribute to the complexity of water resource allocation, particularly in balancing urban supply and agricultural demand.

Conflicts over water diversion rights have emerged in Kurunegala and Anuradhapura, where farmers experience sporadic irrigation access with increasing urbanization-led consumption [2]. Weak enforcement mechanisms have allowed illegal groundwater pumping, worsened regional imbalances, and reduced long-term sustainability. Additionally, an absence of effective monitoring of industrial water usage has led to over-extraction in key production regions, which has further strained freshwater resources.

7. CONCLUSION

Sri Lanka's ancient hydraulic systems remain important to national water security, agriculture, and energy production. This paper reviewed the current state of these systems, noting both their historical strengths and the growing challenges posed by climate variability, urban expansion, and infrastructure degradation. The analysis identified technical limitations, mainly reservoir sedimentation, evaporation losses, pipeline leakage, and the potential for incorporating digital tools such as GIS-based monitoring and predictive flow models. While traditional tank cascade systems continue to offer ecological benefits and decentralization, modern infrastructure does not have the resiliency and efficiency required under current conditions. The findings suggest that combining traditional hydraulic knowledge with modern technologies can improve system performance and resilience. Global examples demonstrate the potential of integrating smart irrigation, automated monitoring, and predictive analytics into water management frameworks. However, implementation in Sri Lanka is hindered due to funding limitations, issues in governance, and gaps in data infrastructure. Addressing these problems requires efforts across policy, engineering, and community levels. Future work should focus on scaling digital tools, improving infrastructure maintenance, and exploring cost-effective adaptations to these solutions. Institutional capacity building and implementation of integrated planning will be imperative in ensuring long-term sustainability and climate resilience for Sri Lanka's hydraulic sector.

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A Critical Review: Challenges and Innovative Solutions in Hydraulic Engineering for Sustainable Water Management in Sri Lanka

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Abstract—The country has relied on advanced hydraulic practices, tracing back to underground tanks and culminating in large, modern reservoirs. Nowadays, the pressure on these systems is increasing. More people living in cities, changing weather patterns, outdated or damaged water systems, and divided responsibilities among organizations hinder effective water management in the country. This study investigates these issues and proposes helpful measures for protecting the significant resource of water in Sri Lanka. The qualitative critical review methodology was chosen, which studied academic, institutional, and technical articles published between 1995 and 2024. The analysis shows gaps in the literature and assesses the accomplishments and failure of the existing hydraulic practices in Sri Lanka, creating a balanced and evidence-based discussion. Its purpose is to observe the state of both rural and urban water systems, point out what is hindering management efforts, and suggest plans to build a stronger and greener water system. It takes ideas from both local and other cultures, using both traditional and new technology for a well-balanced way of farming. The research shows that in the past, Sri Lanka was successful in managing water, but today's systems are strained by increased water usage and unusual weather. Meanwhile, smart water monitoring, harvesting rainwater, solar-powered irrigation, and using community teams are being used with success. The conclusion is that Sri Lanka should combine its age-old wisdom with new ideas and improve the coordination between institutions. More research in the future should include gathering data in real time, using AI to predict weather changes, and designing infrastructure that can withstand climate change to secure water for all areas of the country.

Keywords—Hydraulic Engineering, Infrastructure Challenges, Sri Lanka, Sustainable Water Management

1. INTRODUCTION

The key objectives of the review include historic and contemporary hydraulic practices comparison and assessment in Sri Lanka, key technical, institutional and environmental challenges, and effectiveness of new innovations and management practices, sustainable engineering recommendations that may benefit the policy of long-term water security and the resilience of the whole country.

Water conveyance in civil engineering involves the use of hydraulic systems since the systems supply water, prevent flooding, produce energy, and provide irrigation. Hydraulics engineering employs planned management in the use of water resources, hence advancing the course of human beings and the sustainability of the environment. The necessity of water system optimization has increased over the years due to

increased water requirements and due to Global warming [1]. Having a fairly developed tradition of hydraulic civilization, today Sri Lanka still highly relies on water supply infrastructure. The early civilizations in the region, especially those of the Anuradhapura and Polonnaruwa Era, constructed sophisticated canals and tanks so that they could result in enhanced agricultural production for food as well as population breeding grounds for fast city development [2]. Solutions relevant for the Dry Zone with semi-arid conditions were the Tank Cascade Systems (TCS), which are now recognised as innovative and sustainable all over the world [3]. Sri Lanka is facing a moment is threatens its sustainability in the water structural project. It has barely reached such cities, especially Colombo and Kandy, increasing the pressure on the municipal water supply systems and increasing the chance of urban flooding. Enhancement of urban surface areas by construction, construction in areas considered as flood-prone, and inadequate drainage are factors that have contributed to flood occurrences [4].

Sri Lanka has become more vulnerable to the adverse implications of climate change, such as water level rise and changes in monsoon patterns. While Water security for Colombo is a concern with the Kelani River basin that is threatened by floods currently and unpredictable rainfall, other communities such as Anuradhapura and Polonnaruwa face water scarcity, which is dangerous for the rural economy and food security. Besides climatic and environmental threats, governance and budget restraints form the biggest challenge in the region. Lack of community participation, lack of enough funds for maintenance, and lack of coherent implementation from the institutions spread across many government departments have been the main reasons why water management has not been effective. There is at present an unequal access to service delivery, infrastructure and disasters in the country; notwithstanding the Colombo Water Supply Expansion projects and other Mahaweli Development Program. These complex interactions in the hydraulic systems call for an evidence-based and more robust assessment of Sri Lanka's systems. This research seeks to fill that gap by evaluating the current status of the water infrastructure in the country, both in the urban and rural areas, paying attention to the technical and policy challenges to identify long-term sustainable solutions for the country's peculiar situation in light of socio-economic development and environmental conservation.

2. LITERATURE REVIEW

Hydraulic systems are at the very heart of water supply and control, whether it is in urban or rural areas. These systems have the property of water flowing under pressure, supported by pipes, pumps for circulation, reservoirs for containing this liquid, and valves that regulate the circulation process of the liquid under the principles of fluid dynamics. Hydraulic engineering focuses on learning about water and the mechanisms of energy and flow control. The goal is to develop systems that will give the maximum result by using water in the needed amount without wasting it and ensuring that the needed population's water needs will be met [3]. There is a need to understand the hydraulic systems of water in Sri Lanka. Although in all aspects of life water plays an important role, effectively storing it in a vast system of canals, tanks, and reservoirs is part of the current water conservation system in the country. Conservation of effective and sustainable water systems as a result corresponds with great significance to maintaining sound hydraulic knowledge, especially as complications from urbanization and climate change progress [5].

2.1 Global and Local Practices in Water Supply and Irrigation

Hydraulic engineering can be said to have developed due to the challenges that are faced while trying to control water from around the world. Irrigation systems, proper water use, recycling of water, and desalination plants are practices to ensure that the water supply is secured in the arid regions of the world. For instance, waste in agricultural techniques is reduced by the efficient use of water supply that current irrigation systems, such as drip irrigation, provide. These systems reduce the amount of water used in crop irrigation by automating the distribution of water by using data collected from the soil moisture [1], [6].

Sri Lanka combines centuries-old techniques with contemporary technology in its approach to water management. A new way of managing water, the ancient tank cascade efficiently supplies water in the island country's arid areas. These linked cascade reservoirs are designed to store as much monsoon water as possible so that there will be no wastage and farming can be well facilitated [3]. While these systems have been effective, traditional models such as cascade models are currently under pressure due to issues such as reduced rainfall, poor maintenance, among others. One of such strategies is to use solar pumps since the country aims to reduce the use of fossil fuel in meeting its water needs, following the implementation of renewable energy in the water sector across the globe. As for hydraulic systems, [7] while working in rural areas, access to power may be a problem; therefore, using sustainable energy sources is mandatory for hydraulic system sustainability.

2.2 Modern Trends in Hydraulic Engineering

The most significant has been the increased use of intelligent technologies in the water system. When integrated with Internet of Things sensors, real-time monitoring systems allow engineers to figure out water flow and even find out signs of leakage or poor water use in the pipeline system. These are not only enhancing efficiency but also ensuring prudent, reliable estimation of water supply through demand that is predominated by real-time information [1]. In the construction of hydraulic infrastructures, the concept of 'green infrastructure' has also proven useful in the recent past. Green roofs and blue roofs, bio-swales or planted swales, and constructed wetlands as some of the solutions to be incorporated in the rainwater management so as to reduce pressure on the conventional drainage systems. The strategy of adopting the restoration of wetlands and traditional tanks, provided they were once effective means to regulate water supply in the country, could be an effective and sustainable approach to address the water issues of urban Sri Lanka [4]. Hydraulic system design has been incorporated into the realization of climate adaptation more. More engineers are considering climate adaptation solutions in the form of accommodating more variability in rainfall, for instance, in storage and distribution systems. Due to the increase in sea levels, prolonged storm and drought experiences, fundamental structures require establishment, especially in the coastal and flood-prone areas, because of climate change [5], [8].

2.3 Sustainable Water Management Practices

Hydraulic system design has been incorporated into the realization of climate adaptation. Engineers are considering climate adaptation solutions in the form of accommodating more variability in rainfall, for instance, in storage and distribution systems. Due to the increase in sea levels, prolonged storms and drought experiences,

fundamental structures require establishment, especially in the coastal and flood-prone areas, because of climate change. One of the measures which can be taken to control the use of water resources is the use of rainwater harvesting installations. These systems reduce the dependence on the water delivery system that involves pipes and pipes by collecting and storing rainwater for use in households and farming. Rainwater harvesting has been a practice done in rural areas of Sri Lanka, and integrating the existing water supply system in the urban areas with it would reduce vulnerability to climate variation [9]. Wastewater management involves wastewater treatment and usage for various purposes, as needed to get rid of them for good. Technological advancements have made it possible to safely reuse the water contained in wastewater that is in industries and agriculture for other uses, such as cooling. The other major city within the affected region of Sri Lanka, namely Colombo, and other urban areas, look at wastewater reuse as a potential means of increasing water supply and easing pressure on demand from urban areas [4].

Farmers are even using water more intelligently by adopting modern methods such as the use of sprinklers and drip irrigation systems. They also reduced evaporation and runoff by delivering water to the plant root system, thus ensuring that the water is used where needed most. This form of strategy is vital for the arid zone of Sri Lanka because irrigation and sustained agricultural practices depend upon water preservation [3], [10]. Moreover, having natural ecosystems intact is necessary to sustain the amount and quality of water. Thus, riparian zones, woods, and wetlands filter the water by removing pollutants and sediment from it as well as from the floodplain environment. Further, they also find it useful in managing floods and also help to provide water for the groundwater tributaries. Therefore, it can be understood that such natural barriers are critically important for water security in Sri Lanka for the long term and throughout the world [5].

3. METHODOLOGY

This paper would apply qualitative critical review approach to examining the issues and innovation in the hydraulic engineering industry in Sri Lanka. Academic databases, government reports, and international reports published between 1995 and 2024 were used to collect the relevant literature. Keywords that were used to select the materials included hydraulic systems, water management, climate resilience, and Sri Lanka. The review process entailed the determination of common themes using technical, institutional and environmental dimensions. All the themes were analyzed to contrast between classical and contemporary practices, to evaluate their efficiency and outline the existing voids. The methodology guarantees a holistic but critical comprehension of the ability of the Sri Lankan hydraulic systems to transform into sustainable water management by integrating results of various sources.

4. GEOGRAPHICAL AND CLIMATIC DRIVERS OF HYDRAULIC SYSTEM ADAPTATION IN SRI LANKA

This may be due to its special geographical and climatic conditions experienced in the northern part of Sri Lanka. A large part of the nation is influenced by two dissimilar monsoons, which ruin the geographical distribution of rain. While the southern states get an appreciable amount of rain, the central and northern states face acute droughts. This unequal supply escalates water challenges, especially in the rural areas where the traditional methods of water storage have fallen short of today's requirements [3], [11].

Water delivery systems have been under pressure due to effects such as the urbanization of areas, including Colombo. This has been complicated by these regions' growth in the consumption of water products and pollution of water sources. As stated [4], the ability of cities to adjust to their structures, especially about climatic shocks such as droughts and floods, is tied to urban resilience. The need to make water systems sustainable and functional comes into the understanding that climate resilience must be incorporated into the urban planning formulation. Sri Lanka has embarked on the restoration of renewed water structures, which have proven to be still better compared to the modern facilities, particularly in the rural and semi-urban areas like the village tanks and the cascade irrigation schemes. These designs can be upgraded to fit modern problems while still respecting their history and cultural value, thus using both ancient and modern knowledge concerning technology [12]. The impedance of hydraulic systems in Sri Lanka has been shaped by conventional techniques and contemporary technologies in equal measure. It becomes crucial for the nation to try and find new approaches towards the growing challenges that are posed in the wake of excessive urbanization, climate change, and ageing water systems. To meet future requirements, it will be necessary to apply the modern principles of hydraulic engineering in view of smart technologies, renewable energy sources, as well as rational and sustainable water management approaches. On the other hand, the assurance of the nation's water security will highly rely on the development of traditional water systems such as the cascade irrigation.

5. CONTEMPORARY LANDSCAPE OF HYDRAULIC SYSTEMS IN SRI LANKA

The hydraulic system of Sri Lanka is composed of the country's irrigation systems, or the water management infrastructure that includes the country's water reservoirs. These systems are important since most of a country's revenue is from agriculture as well as from water used in hydropower generation. Sri Lanka has old and new hydraulic systems with which it regulates water for irrigation for agriculture and supply to the cities and industries.

Among the Sri Lankan hydraulic systems, the tank cascade system is as old and has been in existence in Sri Lanka for over 2000 years. These are principally comprised of successive tanks or reservoirs of water that are expected to store the water in anticipation of the rainy season so that the same can be used to supply the necessary irrigation in the dry season. The fact that it has a complex structure and functions as a tank cascade system, the system can now bring water to a larger area with extraordinarily few resources available [13]. Despite the success achieved with these systems, some of them have been abandoned, people's demand increased, while the environment has depleted the effectiveness of many of these tanks. Currently, the objectives of post-modern hydraulic constructions like large reservoirs and dams are flood control, irrigation, rainwater harvesting, and electricity generation. Victoria reservoirs, for instance, Maduru Oya and Kalawewa, are constructed to provide more water supplies and help regulate the seasonal rainfall. Some of which include sedimentation, climate change and effects of urbanization, which the current systems have to combat. Such factors contribute to the challenges faced by these reservoirs in being able to meet increasing demand for water, particularly in urban areas. A significant portion of the electricity consumed in Sri Lanka is also generated by tapping the power of water that is stored in Sri Lanka's streams. Sri Lanka has been increasing the use of renewable energy sources to generate electricity due to the establishment of new hydro

power facilities on rivers such as the Mahaweli and Kelani Rivers, etc. [4]. The use of the hydraulic system of the country, Sri Lanka, is further utilized for electricity generation and water storage for the purpose of irrigation. These systems remain inefficient due to old infrastructures, wear and tear, and the absence of modern technology in handling data and monitoring mechanisms. To ensure the current hydraulic systems in the nation are efficient for managing its people and resources, as well as weather demands that may worsen in future, there is a need for investment in both improvement and deep repair.

6. URBAN AND RURAL WATER SUPPLY NETWORKS: INFRASTRUCTURE AND ACCESSIBILITY

The NWSDB is responsible for providing water to places such as Galle, Kandy and Colombo, which are considered to be industrialized and urbanized and need water more than any other areas. Nevertheless, lost water, which is a result of old age pipes, unapproved connections and leaky and ineffective distribution systems, presents itself as a huge problem, especially for metropolitan regions. It is estimated that up to a third of water is lost before even using it [4]. Another factor threatening the availability of water resources is water pollution from raw sewage, industrial effluents, and agricultural drainage water. A significant portion of the total population of Sri Lanka resides in the rural areas. Much of the time, these regions depend on such sources of water as rivers, comparatively smaller tanks and well-known dug wells. The tank cascade system remains in use, but it continues to deteriorate and provides fewer and fewer solutions to the current methods used in farming. These sources are unreliable in many regions of the country, especially in the arid zone, and during the dry season. Hence, contaminated water due to the absence of treatment plants and appropriate sanitation leads to scarcity of water in rural areas as a frequent problem [1].

Due to the shortcomings of the rural water supply drivers, such as deep well projects and piped water supply in Sri Lanka in recent decades, the government has been attending to this imbalance. However, due to the complexity of the geographic layout and its rural nature in Sri Lanka, the setting up and provision of infrastructure in the rural areas pose a great deal of a challenge in this country [5]. Another challenge now facing the water supply authorities is the cost of laying down water supply networks, especially for the remote areas. Despite the above challenges, other ways of providing water to the rural areas are being considered and trialed, which include the installation of solar water committees for purposes of desalination, as well as rainwater harvesting. There is a need for improvement in the sanitary facilities in rural areas. Lack of proper toilets and other forms of poor hygiene, such as open defecation, expose the communities to waterborne diseases and, in turn, contaminate the water sources. Taking into consideration these facts, the sustainable management of water and sanitation in rural Sri Lanka is crucial in improving the public health status [3].

7. INSTITUTIONAL AND TECHNICAL STRENGTHS OF SRI LANKA'S HYDRAULIC SYSTEMS

Even though they still face many challenges, the hydraulic systems of Sri Lanka offer some benefits that are worth mentioning: One of the main advantages of the tank cascade system is the fact that its beginnings can be traced back a long time, and it has been proven to be efficient. According to the local folklore, they have always been used for farming and controlling floods, as well as for water retention, which is crucial for agriculture [3]. To enhance the aspect of water security, these resources have to be

sustained and advanced concerning their sustainability and resilience. Several years ago, most hydraulic structures could be referred to as old, but in recent years, numerous governmental and foreign investments have resulted in the upgrades of these structures. The above-stated objective has been achieved by providing high priority for the tank rehabilitation and construction of reservoirs to be used for the supply of water for home and agricultural uses in the rural areas. These hydraulic projects' multifunctionality, combining flood control, water delivery, and irrigation, offers flexibility in the nation's water management initiatives. Furthermore, Sri Lanka has gone into the generation of hydropower, where the Mahaweli River has been at the center of hydroelectric power in Sri Lanka. Hydropower contributes to more than 50% of the total electricity needs of the country, which is a renewable energy source which is critical in reducing reliance on fossil energy as well as greenhouse gas emissions [4]. Following the issues discussed above, it can be concluded that Sri Lanka has sufficiently developed hydraulic installations for water storage for irrigation as well as energy production. The governance of Sri Lanka's water resources can also be considered an advantage for the country's water management. Although the NWSDB is focused on water supply and quality for the urban sector, other bodies in Sri Lanka can be classified as executing significant irrigation work, such as the Sri Lanka Irrigation Department. Today's irrigation and water supply projects in the country, the technical support and financial resources that are needed to develop and implement, have been provided by the institutional formation in collaboration with the support of international organizations such as the World Bank and the Asian Development Bank (ADB).

8. SYSTEMIC WEAKNESSES AND CRITICAL GAPS IN WATER RESOURCE MANAGEMENT

The hydraulic systems have pleasure of following features, but for the sustainability of water security, some strengths require some improvement and weaknesses that need to be addressed and filled. Infrastructure degradation is one of the most serious challenges. Most of the existing water delivery lines, canals, and reservoirs have been in Sri Lanka for a long time, and their efficiency has been threatened by sedimentation and lack of maintenance. While the authorities have pinned efforts on modernizing and reviving some of these systems, there is still a long way to go to upgrade and protect the present sanitation. Climate change effects can be considered as another fundamental demarcation factor. High emphasis can be placed on the fact that Sri Lanka is one of the countries that would suffer from the effects of global warming most of all, as it has become very vulnerable to climate change due to increasing rainfall volatility, prolonged dry season, and heavy monsoon rains. Some of the climate changes which are affecting the reliability of water supplies are as follows: Climate changes make it even harder to keep dependable water systems in place, especially in rural areas where they are already struggling to deliver water regularly. It has been noted that [5] state that the problem of droughts has increased further as influenced by rainfall fluctuations, most especially in the dry zone in Sri Lanka, and that the water supply in these homes, as well as its usage for agricultural purposes, has been affected.

Regarding water management, there are threats associated with the fragmented institutional structure. Different aspects of the water delivery range from irrigation to the provision of drinking water, and this is managed by many organizations and limited local authorities, leading to ineffective and disjointed operations. There is an option of implementing Integrated Water Resources Management, known as IWRM, that would

help in improving the currently available arrangements and ensure sustainability in the water systems of the nation [1]. The greatest challenges that people face when it comes to sustaining and expanding the hydraulic systems are a lack of funds. The increase in the costs of developing infrastructure, particularly in the remote areas, remains a challenge to Sri Lanka's growth despite the grants and loans it received from friendly countries. Advanced technology like data analytics and automatic systems of water management that might enhance the sustainability of water management are also restrained due to a dearth of adequate funding [4].

The hydraulic systems in Sri Lanka are at a critical juncture, wherein they could either choose to pursue a positive growth path or a negative growth path. While the nation has learnt the management of its water resources traditionally with traditional facilities, including tank cascades, more of the modern problems, such as urbanization, global warming, and degradation of infrastructure, need a quick response. Despite recent improvements in contemporary extension and enlargement of water systems, sustainable water management in the following decades will rely on improvements in technology, reinvention of the earlier systems, and organizational relationships. Most of these challenges can be attainable by implementing proper water resources management strategies that would ensure the hydraulic infrastructures respond to Sri Lanka's increasing population, the emerging trends of urbanization and climatic changes as well.

Although these weaknesses have been captured adequately, there is a lack of studies comparing them based on their effects or examining their interdependence. This review concludes that infrastructure deterioration and institutional fragmentation are reinforcing to each other: poor coordination increases infrastructure deterioration and poor maintenance constrains policy implementation. Therefore, in order to overcome these issues, it is necessary to have combined reforms that not only cut across technical, administrative, and financial sphere but also to consider them not as separate problems.

9. CRITICAL CHALLENGES IN SRI LANKA'S HYDRAULIC ENGINEERING SECTOR

9.1 Impacts of Climate Change on Hydraulic Systems

Hydraulic systems in Sri Lanka struggle with the strongest climate change impacts. Sri Lanka relies primarily on rain for both farm work and freshwater production. Climate change causes more frequent and stronger droughts plus floods to happen worldwide. The government struggles to control water resources because the changing rainfall has both extended dry seasons and produced more rain during typical wet months [5] [12]. This study has shown that these shifting hydrological weird patterns are affecting key infrastructure, such as irrigation systems, canals, and reservoirs, among others. Strong rains often cause floods and water waste, and on the other hand, reservoirs are unable to fill to the full during the dry season due to not particularly good rainfall [1]. Overall, these weather variations may have a significant impact on the availability of water for industrial and human consumption and irrigation.

9.2 Urbanization and Escalating Water Demand

Over the past decades, Sri Lanka has become an urbanized country, and such a phenomenon increases the water demand, in large cities such as Colombo. This is due to increased need for drinking water and the need for water for industrial activities because of urbanization and population growth. This has placed a great deal of stress upon the

nation's current water supply systems, which were built to serve smaller populations [4]. The growth of cities like Colombo has contaminated local water supplies. More often than not, there has never been before and there never will be sewage, industrial trash, plastic garbage that is dumped into rivers and lakes and leads to further degradation of water quality and health risks [1], [5].

9.3 Infrastructure Ageing and Maintenance Challenges

Many Sri Lanka reservoirs, dams, and ageing irrigation networks require repair and improvement. Since the colonial era, a great deal of the nation's water infrastructure has been built, including much of it meant to regulate the water flows absent regard to future urbanization and the consequences of climate change. Over time, these systems have not been properly maintained and lack modern technology [8]. The infrastructure maintenance and regrowth should be considered a priority that the government should address. This means, of course, that dams and canals are designed to run as long as possible, and that entails routine inspections, repairs and application of modern engineering techniques. Also, smart infrastructure technology, which includes sensor-based hydraulic performance real-time monitoring systems, may be adopted in Sri Lanka. Preventative maintenance and repairs would be possible faster, and so expensive malfunctions can be prevented [3] [13].

9.4 Environmental Degradation and Resource Sustainability

Environmental degradation in Sri Lanka's watershed areas is exceptionally large due to the expansion of agriculture, deforestation and urban growth. Soil erosion, deforestation and the loss of wetland areas have adversely affected the natural environment's capacity to absorb and control water. As a result of that, the sedimentation has increased in rivers and reservoirs, hence their capacity to store water and also the flow of water has become slower [3]. Agricultural runoff, normally containing fertilizers and pesticides, is contaminating water sources that are resulting in them becoming unsuitable for use in both agriculture and for humans [1] [12]. There is a need for a total approach to watershed management. Among these are reforestation projects, environmentally friendly techniques of land management and the creation of buffer zones around water sources in order to stop water pollution. Encouraging environmentally friendly agricultural practices like integrated pest management and organic farming can curb the damage brought to the quality of water from agricultural runoff [7].

9.5 Data Limitations and Gaps in Monitoring Infrastructure

The major problem facing Sri Lanka's hydraulic systems is the lack of adequate data and available monitoring infrastructures. Although the number of reservoirs, irrigation systems and bodies of water is great, the methods of collecting data are not always exhaustive, precise or timely. One shortcoming of this is that making the right decisions concerning our water will be significantly harder when there is a potential for flooding or water scarcity. For example, hydraulic systems are difficult to evaluate regarding the condition and functionality when there is no real-time monitoring, like pollutants, sediments and climate changes [3]. However, to monitor water quality, flow and availability, Sri Lanka has to invest in state-of-the-art data collection methods, such as satellite information, sensor networks, and remote sensing technologies. The incorporation of geographic information systems (GIS) can also greatly aid in mapping and analyzing water networks across the nation. This will help the nation better forecast

possible problems such as water shortages, contamination or system breakdowns by increasing data collection and installing real-time monitoring systems. This will help to bring about more responsive and flexible water management techniques [1] [13].

Comparative analysis shows that, despite the fact that in the past, the Sri Lankan hydraulic sector has been highly resilient, it has fallen behind the other regional actors like India and Thailand in emulating adaptive and data-driven water systems. The imminent rate of modernization and disunited digital surveillance systems remain a threat to effective decision-making and real-time management of resources.

10. INNOVATIVE ENGINEERING SOLUTIONS FOR HYDRAULIC SYSTEM ENHANCEMENT

10.1 Infrastructure Upgrades and Innovations

Upgrading and innovating Sri Lanka's water infrastructure is necessary to tackle the issues, aged infrastructure and climate change. Sri Lanka should consider the implementation of innovative hydraulic engineering solutions to improve the effectiveness of current systems as well as to avoid developing new sets of systems in order to deal with strains of an expanding population and a changing climate. Use of multipurpose reservoirs is also more flexible in the management of water resources as they simultaneously store water for use and produce energy. If hydroelectric parts are added to Sri Lanka's current reservoirs, India would be meeting its energy and irrigation needs, and the country's economy would be boosted in two ways. Also, the government should go further to investigate the application of desalination technology in meeting the increasing demand for water in the urban areas, mostly coastal regions [7] [13].

10.2 Sustainable Water Management Strategies

To ensure that Sri Lanka's water resources are made available in the long term, sustainable water management techniques must be applied. It also means focused demand-side water use in addition to improved infrastructure in the water supply. Sri Lanka should adopt a comprehensive approach allowing for a resource-based, water quality-based and efficient use of water. Small-scale water storage systems and rainwater collection can aid the central water systems in rural areas. Drip irrigation, along with precision farming, will help in improving agricultural water usage efficiency, resulting in the same excess water being conserved and unnecessary waste being reduced. Promoting agricultural diversity, which does not heavily depend on crops that rely heavily on water consumption, can also offer support to sustainable water use [5][10].

10.3 Policy and Institutional Reforms

However, even engineering solutions are vital but not sufficient if successful water management programs are to be assured, and this calls for effective policy and institutional reforms. In Sri Lanka, clear water management policies which put the sustainability, resilience and fairness in water distribution first must be developed. Those include implementing regulations to keep out excessive water extraction on key sources, enhancing monitoring systems and regulating water usage more. Apart from that, the capability of organizations in control of the resources of water, namely the National Water Supply and Drainage Board and the Sri Lanka Mahaweli Authority, should be strengthened. These organizations, however, need to have the required tools and

training to efficiently manage water systems in the face of the persistent problems [4] [8].

10.4 Community-Based Water Resource Management

A more community-driven approach to water management would help improve the sustainability of water systems, especially in rural areas. Participatory approaches that enable the local people to manage their water resources have been proven to work globally [1]. By setting up local water committees to educate local stakeholders on our water conservation processes, taking local communities on board when making decisions on our water resources. The ability and experience of the local community are sure to cover the specifics of the particular requirements of every local populace that will drive water administration plans oriented to a sense of possession and in charge in this sense [3].

10.5 Smart Water Systems and Automation

Integrating automation and Artificial Intelligence (AI) in smart water systems is one of the promising ways of enhancing hydraulic systems in Sri Lanka for the ease and convenience of the public. They take a real-time approach to optimizing the water distribution and use by combining information from various sources, such as water flow sensors, weather forecasts and consumption patterns. Demand patterns can be predicted on the basis of AI-based algorithms, and water should be distributed accordingly to avoid any water waste and make the best use of water resources. It can also detect network anomalies and leakage and act within the shortest time by an automated system. Nevertheless, the use of Internet of Things (IoT) devices is beneficial for ensuring reliable water monitoring or monitoring within the urban and rural water systems, with better water resource management. There is the ability to couple this technology to irrigation systems to measure soil moisture and control irrigation schedules to waste less water and make sure crops are being irrigated to the appropriate degree [11]. Considering the real-time monitoring of water quality and consumption tracking, and predictive analytics, Sri Lanka should give higher priority to developing smart water networks based on sensor networks and AI. This innovative technology could help Sri Lanka transform its water management system to become data-driven, more automated, and help improve resilience to the changing climate conditions, reduce losses, and increase efficiency through upgrading infrastructure [4] [1].

However, in spite of the bright future of these technologies, massive application in Sri Lanka is not very common because of financial limits, insufficient technical capacity, and institutional responsibility being scattered. The majority of digital or AI-based systems are at pilot stage at the moment. Critical assessment reveals that unless these innovations are nationalized in terms of integration and harmonization of funds, they may end up as mere concepts and not as revolution.

10.6 Study Limitations

The research is carried out using secondary data and qualitative synthesis. The lack of recent performance records on most local hydraulic projects and the disperse manner in which government records were available hampered the thoroughness of quantitative analysis. In addition to this, the validation was not done in the field and therefore, results rest on the validity and representativeness of literature reviewed. To complement these

qualitative perspectives, future research must combine primary data gathering, interviews with the stakeholders, and quantitative modelling.

11 CONCLUSIONS

Sri Lanka's hydraulic systems are key to the country's development and particularly to urban planning and agriculture, as Sri Lanka relies on irrigation networks and water supply infrastructure. Although these systems have progressed over the past few decades, keeping and improving the efficiency, sustainability, and resiliency of the systems, for instance, in the light of resource constraints, climate change, and a growing population, is difficult to do.

1. Sri Lanka's economy is dominated by hydraulic infrastructure, such as water delivery networks, irrigation systems, and reservoirs. These systems facilitate urban water supply, power generation and agriculture in realizing sustainable development.

2. Climate change poses an additional challenge for Sri Lankan hydraulic engineers. These issues adversely impact the functioning and reliability of existing systems and have become more rainfall unpredictability, rising temperature and increasing frequency of droughts and floods.

3. The existing Sri Lankan hydraulic systems have strong negatives, including ineffective water distribution, a shortage of flood infrastructure and vulnerability to extreme weather attributed to climate change. Moreover, urbanization and fast industrialization impose pressure on water supplies.

4. Continuous programs have to be conducted to modernize the water management systems utilizing the latest technology, such as climate-adaptive infrastructure, GIS-based water management works, and remote sensing. Another essential step in dealing with future problems involves the creation of a practice of sustainable water management, like water-efficient irrigation techniques.

12. CRITICAL REFLECTIONS

It is evident from today's consideration of Sri Lanka's hydraulic systems that both advancements and enduring difficulties are present. Sri Lanka has been able to devise a network of hydraulic systems with adequate and necessary services in bulk; however, such networks are disconnected and play an inadequate strong in supporting the modern world's demands. However, these systems are seriously threatened for their sustainability by the nation's expansion of population, its urbanization and the impact on these systems of the uncertain effects of climate change.

The results highlight that even though Sri Lanka has a rich hydraulic heritage, to operate these systems in the contemporary context is necessary to re-examine the governance structures in addition to modernization of the technical. The integrated approach in water resource management is required, in which all sectors (Agriculture, Energy, Urban water supply) cooperate and strive for common goods. In today's scenario, silos have started appearing between various stakeholders and in the government that causes inefficiencies and does not utilize resources in the optimum manner. Moreover, though these supposed historical successes of such things as irrigation systems and reservoirs

readily fit the stresses of ageing infrastructure and climatic change. To cater for the imminent problems, the water systems of Sri Lanka must be able to withstand new, more flexible and robust solutions.

13. FUTURE RESEARCH DIRECTIONS

For future research, several areas of further research are needed to improve hydraulic systems in Sri Lanka are looking forward. There is still more work that needs to be done to illuminate exactly how changes to both precipitation patterns and rising temperatures will influence water availability in varying areas of Sri Lanka. Real-time data collection, AI-based forecasting systems and smart irrigation systems can help leverage newer technologies in water management to save the utility. For long-term hydrological modelling, comprehensive models can provide long-term climate trends and impacts on water systems will be useful in the design and operation of the resilient infrastructure.

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A Feasibility and Sustainability Assessment of Timber-Based Residential Construction in Sri Lanka

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Abstract— Over the years, the construction industry has caused an increase in climate change, with 40% of global energy consumption and almost 1/3 of greenhouse gas emissions. This study assessed the sustainability and feasibility of timber-based residential construction in Sri Lanka, a significant research gap in the local context. To address the cultural, economic, and environmental dimensions of this gap, a mixed-methods approach with quantitative surveys (n=20) and qualitative interviews of professionals in the field was used. People emphasize timber's aesthetic qualities and understand its environmental advantages and construction potential, with 90% and 80% of respondents supporting timber's use in housing construction. Barriers of inadequate resources, poorly defined regulations, a culturally derived shortage of skilled labor, and cultural, especially in concrete construction, remain. This study argues that timber should underpin Sri Lanka sustainable residential construction. This will help Sri Lanka development to meet the sustainable goals of climate change.

Keywords—Timber construction, Sustainable building materials, Residential construction, Environmental sustainability, Construction feasibility

1. INTRODUCTION

In recent years, the world's construction sector has had to deal with new major environmental hurdles, including the fact that buildings use 40% of the worlds energy and produce nearly 1/3 of the world`s greenhouse gas emissions (GHGs) [1]. Emissions are primarily from the use of cement and steel in construction, which are the most low-cost and high impact building materials throughout the life cycle of buildings. Steel and iron production emit around 7% of global CO_2 emissions, and cement production adds 5-10% [2]. This significant environmental impact calls for the urgent need for low carbon solutions and increased material efficiency.

Potential solutions to this problem are materials that are sustainable and are environmentally friendly because of their energy use efficiency, recyclability, and responsible resource use. Timber is seen as a low carbon alternative for construction because of the energy saved when using it compared to concrete and steel in the extraction, production, and construction phases, along with its renewability and durability [3]. Timber has also been enhanced by modern engineered wood products which include Cross-Laminated Timber (CLT) and Glue-Laminated Timber (GLT). This has transformed timber construction positively for the multi-story buildings in countries with sustainable forestry such as Sweden and Canada. [4].

Sri Lanka has a long tradition of wooden construction evident from the historical Lovamahapaya, a nine-story wooden structure built by King Dutugemunu 2 centuries

B.C. [5]. The construction of such structures was facilitated by the generous availability of locally sourced wood, the manipulation, joining, and extensive craftsmanship of wood, as well as the bespoke furniture traditions of the country. Traditionally, Sri Lanka was also home to integrated wood buildings and wooden construction dominated the country. However, modern residential construction has shifted towards cement block walls, concrete floors, and rubble masonry with wood being relegated to non-structural doors and windows [6]. The sustainable use of building materials has been appreciated, albeit the construction material landscape of Sri Lankan buildings lacks extensive research [7]. This research seeks to fill this gap by analyzing the potential for and the feasibility of sustainable, timber residential construction in Sri Lanka, establishing timber as a sustainable construction, low-carbon building material aligned with internationally recognized sustainability frameworks.

2. LITERATURE REVIEW

2.1 Energy Challenges in Building Construction

Energy efficiency has become a critical priority across sectors, with residential buildings alone responsible for 17% of greenhouse gas emissions and 27% of global energy consumption [8]. Life Cycle Energy Analysis (LCEA) reveals that the embodied energy of building components- encompassing extraction, processing, transportation, construction, maintenance, and end-of-life phases- significantly contributes to the total life cycle energy [9]. Research in Lebanon, for example, demonstrated that transport energy accounted for 49% of the total life cycle energy demand, overshadowing operational energy (33%) and embodied energy (18%) [9].

2.2 Sustainable Construction Practices

International agreements like the Paris Agreement (2015) and frameworks like UN Sustainable Development Goal No. 7 underscore the global commitment to sustainability, expecting energy efficiency improvement rates to rise substantially [10]. Sustainable construction prioritizes resource conservation, aiming to meet present needs without compromising the ability of future generations to meet theirs. This has led to the adoption of modern sustainable materials, including timber, recycled steel, and high-performance concrete, which minimize environmental impacts while enhancing structural performance [11]. Although these materials often entail higher initial costs, they provide long-term savings through reduced maintenance and operational expenses. Techniques such as prefabrication and modular construction further bolster sustainability by maximizing material use, minimizing waste, improving energy efficiency, and reducing transportation-related emissions [10], [11].

2.3 Timber in Construction

Life-cycle assessments consistently demonstrate that mass timber structures emit fewer greenhouse gases over their lifespan, positioning timber as a key component of low-impact, energy-efficient buildings [12]. This sustainable alternative to traditional materials provides substantial advantages through carbon storage and lower CO_2 emissions during production, construction, and use phases [13].

Main timber products in construction include:

- Cross-Laminated Timber (CLT): Manufactured from timber layers arranged perpendicularly, providing dimensional stability and strength
- Glue-Laminated Timber (Glulam): Composed of wood layers arranged in parallel, used for decking, beams, and columns
- Nail-Laminated Timber (NLT): Constructed from stacked timber secured with screws or nails, typically used for roofs and floors
- Dowel-Laminated Timber (DLT): Secures timber boards with dowels rather than nails

Famous projects like Brock Commons Tower in Canada and Stadthaus Murray Grove in the UK demonstrate timber's benefits in reducing construction time, improving thermal efficiency, minimizing weight, and lessening environmental impact [14].

2.4 Timber Construction Advantages and Disadvantages

Research comparing mass timber with traditional concrete and steel construction reveals several key findings. Mass timber structures achieve 18% lower global warming potential despite 7% higher cumulative energy demand due to CLT's higher energy use [12]. Construction times are 5% faster than traditional concrete-steel systems [1].

Advantages include:

- Thermal properties are sixteen times greater than those of concrete buildings
- Wood waste repurposing for construction materials or energy production
- Cost and time efficiency through prefabricated panels
- Economic stimulation through local manufacturing jobs
- Improved safety through prefabrication and smaller workforces

Disadvantages include:

- 36% more gypsum board required for fire-resistance standards
- Technical challenges with local hardwood species development
- Up to 6% higher costs than traditional buildings
- Safety concerns, including fire hazards and product defects
- Biological and corrosion hazards requiring mitigation

2.5 Timber Resources in Sri Lanka

Sri Lanka's timber resources originate from both forest and non-forest sources. Natural forests and plantations provide forest timber, while rubber and coconut plantations are significant non-forest sources [15]. Natural forest cover constitutes 29.7% of the land area (1,951,473 hectares), encompassing dense forests, open forests, mangroves, and savannahs.

Between 2017 and 2019, the State Timber Corporation harvested annual averages of 31,000 m^3 of teak and 34,000-36,000 m^3 of pine. However, approximately 70% of industrial timber now comes from non-forest resources, including home gardens, rubber, and coconut plantations. Home gardens, spanning over 858,000 hectares, supply 40% of timber, though the wood is often of lower quality [5].

Currently, timber usage in Sri Lankan construction is concentrated in roofing (42%), doors and windows (38%), and furniture (19%). The industry faces numerous challenges, including excessive regulation, inconsistent policies, weak supply chains, a negative public perception, a lack of data, outdated technology, and a shortage of skilled workers [5].

3. METHODOLOGY

This research employed a mixed-methods approach, integrating quantitative and qualitative techniques to comprehensively assess the feasibility and sustainability of timber-based residential construction in Sri Lanka.

3.1 Research Design

The mixed-methods design leveraged advantages of both quantitative and qualitative approaches. The quantitative component involved surveying the general public to gather opinions and preferences regarding timber-based residential construction through closed-ended questions distributed via email and social media. The qualitative component conducted detailed interviews with industry professionals, including contractors, suppliers, quantity surveyors, and architects, through video meetings to investigate technical, financial, and policy-related aspects.

3.2 Data Collection

Quantitative Survey: The public survey was structured into six sections:

1. Demographics (age, gender, income, location, residence ownership, education)
2. Awareness of timber-based construction
3. Perceptions of timber-based construction benefits and concerns
4. Cost and affordability considerations
5. Timber availability and local practices
6. Adoption potential of timber in Sri Lanka

Qualitative Interviews: Professional interviews covered seven key areas:

1. Background information and experience
2. Technical feasibility assessment
3. Economic considerations and timber availability
4. Cultural and regulatory perspectives

5. Skilled labour availability and training needs

6. Sustainability and adoption strategies

7. Challenges and recommendations

3.3 Data Analysis

Quantitative survey data was analyzed using descriptive statistics with Microsoft Excel, identifying patterns, relationships, and demographic variations. Qualitative interview data underwent thematic analysis to extract key insights regarding feasibility and sustainability factors.

4. RESULTS AND DISCUSSION

4.1 Results

4.1.1. Demographic Profile

The survey attracted 20 respondents with the following characteristics (Figure 1):

• Age Distribution: 90% aged 20-30, suggesting strong younger generation interest in sustainable construction

• Gender: 80% male (16 respondents), 20% female (4 respondents), reflecting male dominance in construction-related topics

• Education: 55% held bachelor's degrees, 40% had diplomas/certificates, indicating a highly educated sample likely more receptive to sustainability concepts

• Residence Ownership: 85% owned their residences, suggesting investment-oriented perspectives and decision-making authority

• Location: 50% suburban, 35% urban, 15% rural, providing diverse geographic perspectives

• Income: 40% earned above Rs 200,000 monthly, 20% below Rs 50,000, with middle-income representation across other brackets

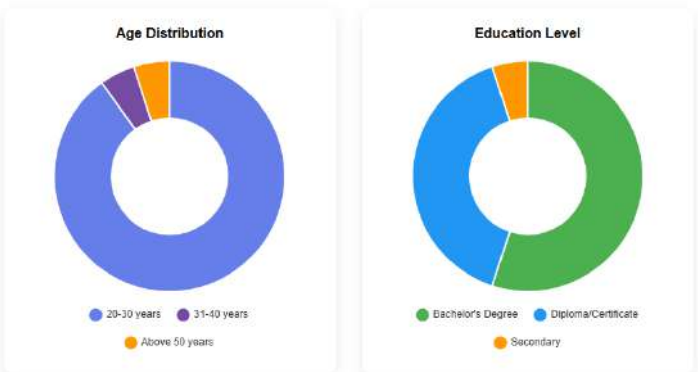

Figure 16- Survey Respondent's Demographics

4.1.2. Awareness and Perceptions

Awareness levels proved remarkably high, with 90% of respondents aware that timber can be used for residential construction. Additionally, 85% had experience seeing or living in houses with timber elements, suggesting substantial exposure to timber applications. Regarding observed timber elements, the most comprehensive combination (walls, roof, doors, windows, floors, columns, and beams) was noted by five respondents. In comparison, four respondents observed timber in "roof, doors, windows, floors" and "walls, roof, doors, windows, floors" combinations. Figure 2 below shows the details regarding public awareness and perceptions regarding timber construction.

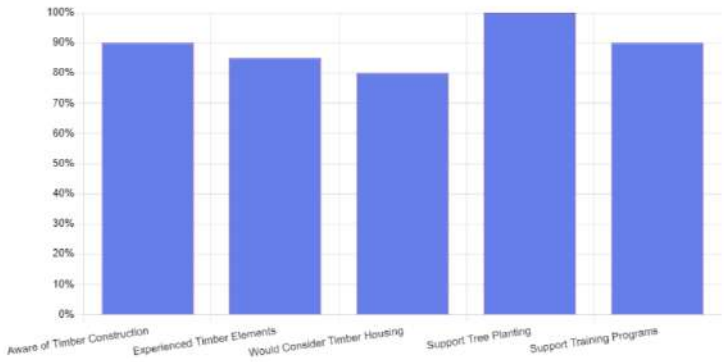

Figure 17- Public Awareness and Perceptions of Timber Construction

Perceived Advantages: The combination of "eco-friendliness and aesthetic appeal" emerged as the most recognized advantage (7 respondents), highlighting environmental consciousness and visual appreciation as primary motivators. Concerns: The most comprehensive concern combination," fire safety, termite issues, durability in climate, and cost," was expressed by four respondents, while three respondents each cited "termite issues and durability in climate" and "cost" alone as primary concerns.

4.1.3. Acceptance and Willingness

A strong 80% of respondents (16 individuals) would consider living in houses with more timber elements, with only 20% responding "maybe" and none definitively refusing. Among those willing to consider timber construction, the preferred elements were "roof, doors, windows, floors" (6 respondents) and comprehensive structural systems (3 respondents).

4.1.4. Cost Considerations

Cost sensitivity analysis revealed nuanced attitudes:

• Equal Cost Preference: Only 15% definitively preferred timber at equal cost, while 55% responded "maybe," suggesting cautious optimism requiring additional persuasion

• Cost Perception: 65% believe timber houses are more expensive than conventional alternatives

• Price Sensitivity: 60% would consider timber construction if 10-20% cheaper, demonstrating significant price elasticity

• Environmental Premium: Responses split evenly (40% yes, 40% no, 20% maybe) regarding willingness to pay extra for environmental benefits.

4.1.5. Resource Availability and Climate Suitability

Resource availability perceptions showed considerable uncertainty: 40% were unsure about Sri Lanka's timber resources adequacy, 35% believed resources were insufficient, and only 25% expressed confidence in resource availability. However, environmental commitment was unanimous, with 100% supporting increased tree planting for sustainable timber use and 90% supporting timber construction training programs for local workers. Climate suitability received a positive assessment, with 65% believing timber construction suits Sri Lankan climate conditions, while 35% remained unsure.

4.1.6. Government Support and Adoption

Future adoption showed strong conditional support: 95% would support timber-based residential buildings if affordable and sustainable, and 65% would consider timber houses with modern features and durability.

Government encouragement received mixed responses: 50% supported government promotion, 45% were unsure, and only 5% opposed government involvement, suggesting a need for more transparent policy communication.

4.1.7. Professional Interview Insights

Cultural Acceptance: Professionals identified strong cultural bias favoring concrete construction, associating it with modernity, safety, and permanence. Timber is often perceived as rural, temporary, or outdated material, creating significant adoption barriers despite demonstrated global success.

Technical and Regulatory Readiness: Major gaps exist in building codes and technical guidance for timber as load-bearing material. Lack of uniform regulations, certification organizations, testing laboratories, and product grading systems for local wood varieties severely limits professional confidence in timber applications.

Skills and Workforce Development: Significant skills gaps exist throughout the construction value chain. While traditional carpentry expertise exists, structural timber construction knowledge is limited. This extends from site labor to supervisors, engineers, and building inspectors, creating quality and safety concerns.

Sustainability and Future Potential: Professionals acknowledged timber's environmental benefits and alignment with global sustainability trends. However, practical feasibility depends on systematic improvements including local supply chain development, cost competitiveness, regulatory support, and institutional backing through pilot projects and financial incentives. Figure 3 below represents a Comparative analysis of timber and conventional construction across multiple parameters.

Parameter	Timber Construction	Conventional Construction	Advantage
Carbon Footprint	18% lower global warming potential	Higher CO_2 emissions	Timber
Construction Time	5% faster completion	Longer construction periods	Timber
Thermal Performance	16x better insulation properties	Poor thermal performance	Timber
Initial Cost	Up to 6% higher upfront cost	Lower initial investment	Conventional
Weight	68% of concrete building mass	Heavier structure	Timber
Fire Resistance	36% more gypsum board needed	Better fire resistance	Conventional

Figure 18- Timber vs. Conventional Construction Comparison

4.2 Discussion

4.2.1. Timber Construction Performance

The findings align with global evidence supporting timber's advantages in construction efficiency, thermal performance, and environmental impact. Interview participants highlighted its lightweight nature and prefabrication potential, which reduce labor intensity and project timelines—a benefit confirmed by literature showing shorter build times and lower life cycle energy compared to heavier materials [16]. The perceived thermal advantages are consistent with research on CLT's superior thermal resistance [17], and life cycle assessments robustly demonstrate timber's reduced embodied carbon and greenhouse gas emissions relative to steel or concrete [18, 19].

4.2.2. Adoption Barriers in Sri Lanka

Multiple interconnected barriers limit timber adoption in Sri Lankan residential construction:

Cultural Barriers: Deep-rooted cultural bias favors concrete as representing modernity, permanence, and safety. This perception parallels international cases where cultural perceptions significantly impede timber adoption [20], particularly in regions unaccustomed to timber construction.

Technical and Skills Limitations: While Sri Lanka possesses traditional carpentry expertise, knowledge of structural timber systems is lacking. This aligns with research showing limited timber-specific training and building standards constraining timber technology acceptance in tropical regions [21].

Regulatory Inadequacy: Building codes provide minimal timber guidance, creating uncertainty and stifling innovation. Unclear regulations and poor institutional understanding of engineered timber systems prevent implementation in developing contexts [22].

Supply Chain Challenges: Underdeveloped local supply chains necessitate import dependence. This reflects broader challenges in tropical countries facing uncertain timber trade with poor forestry management and limited sustainable plantation investment [23].

Climate Concerns: Skepticism regarding timber durability in Sri Lanka's tropical climate reflects legitimate concerns about biodeterioration risks from fungi, insects, and moisture, requiring advanced preservation techniques for longevity assurance [24].

4.2.3. Resource Availability Assessment

Sri Lanka possesses ecological potential for timber-based construction through diverse species, including traditional options (Teak, Mahogany, Jak) and fast-growing alternatives (Albizia, Lunumidella, Eucalyptus, Rubberwood). However, consistent availability, quality control, and supply logistics remain problematic [2].

Natural forest timber reliance has declined, with a movement toward plantation species and sustainable sources. Home gardens spanning 858,000 hectares supply 40% of timber, though predominantly low-quality material. Limitations often hinder the implementation of alternatives in processing infrastructure, technical species data gaps, and limited commercial supply chain promotion.

Supply chain management complications arise from the absence of national data banks and inconsistent management practices. However, expansion potential exists through plantation forestry and composite timber technologies. Expert recommendations include plantation policy improvements, investments in laminated timber production, and support for agroforestry programs.

4.2.4. Current Application Patterns

Timber usage in Sri Lankan construction remains concentrated in non-load-bearing elements: roofing (42%), doors and windows (38%), and furniture (19%). Roof construction represents the most prominent structural application, particularly in single-story housing using species like Coconut and Kempas timber for rafters, purlins, ridges, and wall plates.

Innovation trends indicate movement toward engineered timber products, including finger-jointed wood and laminated panels. These alternatives promise reduced raw timber usage while extending lower-grade timber usability. However, utilization remains constrained by performance data gaps and regulatory limitations for newer applications.

Traditional timber construction analysis in heritage structures demonstrates climate-suitable techniques that could inform modern applications through integration of vernacular wisdom with contemporary engineering approaches [25].

5. RECOMMENDATIONS

Based on research findings, the following strategic recommendations could facilitate timber-based residential construction adoption in Sri Lanka:

5.1 Policy and Regulatory Reform

Building Code Revision: Comprehensively updated national building codes to include specific provisions for structural timber use, enabling legal approval of timber designs without unnecessary delays or uncertainties. Establish clear technical standards for engineered timber products, including CLT, GLT, and hybrid systems.

National Timber Policy: Develop comprehensive policies promoting sustainable timber supply through plantation development, forest management improvement, and supply chain optimization. Integrate timber construction promotion within national housing and environmental policies.

Regulatory Streamlining: Simplify permit processes for timber construction while maintaining safety standards. Establish clear guidelines for timber species selection, treatment requirements, and structural applications suitable for local climatic conditions.

5.2 Supply Chain and Resource Development

Sustainable Forestry: Invest in plantation forestry expansion focusing on fast-growing species suitable for construction applications. Develop sustainable harvesting practices, ensuring long-term resource availability while maintaining ecological balance.

Processing Infrastructure: Establish modern timber processing facilities capable of producing engineered wood products, including laminated timber, finger-jointed products, and composite materials. Invest in quality control systems and grading standards for construction-grade timber.

Supply Chain Integration: Develop integrated supply chains connecting plantation forests, processing facilities, and construction markets. Establish reliable distribution networks, ensuring consistent availability of construction-grade timber throughout the country.

5.3 Workforce Development and Training

Professional Education: Integrate timber construction modules into architectural, engineering, and construction management curricula. Develop specialized courses covering modern timber technologies, design principles, and construction techniques.

Vocational Training: Establish comprehensive training programs for carpenters, site supervisors, and construction workers covering structural timber systems, modern joinery techniques, and quality control practice partner with international experts to transfer technological knowledge.

Certification Programs: Develop professional certification systems for timber construction specialists, ensuring competency in modern timber technologies and construction practices.

5.4 Public Awareness and Demonstration

Education Campaigns: Launch comprehensive public awareness campaigns demonstrating timber construction benefits, including environmental advantages, cost effectiveness, and modern aesthetic appeal. Utilize multiple media channels for maximum reach.

Demonstration Projects: Implement government-sponsored pilot housing projects showcasing timber construction feasibility, sustainability, and modern design integration. Create visitor centers and educational facilities, allowing public interaction with timber technologies.

Success Story Promotion: Highlight international timber construction successes relevant to the Sri Lankan context, emphasizing climate adaptability, cost effectiveness, and architectural possibilities.

5.5 Research and Development

Climate Adaptation Research: Conduct comprehensive studies on timber performance in the Sri Lankan tropical climate, including durability testing, pest resistance evaluation, and fire safety assessment. Develop climate-specific treatment and protection techniques.

Hybrid System Development: Research timber-steel and timber-concrete hybrid systems, optimizing structural performance while addressing local concerns about strength and durability. Develop locally appropriate composite solutions.

Economic Analysis: Conduct detailed cost-benefit analyses comparing timber construction with conventional alternatives throughout building lifecycles. Include environmental cost considerations and long-term financial benefits.

5.6 Financial Incentives and Support

Construction Incentives: Provide tax incentives, subsidies, or low-interest loans for timber-based residential construction, encouraging early adoption. Develop green building certification programs that recognize the environmental benefits of timber construction.

Research Funding: Establish dedicated funding streams for timber construction research, including academic institutions, private sector partnerships, and international collaboration initiatives.

Industry Development: Support private sector investment in timber processing, manufacturing, and construction capabilities through financial incentives and technical assistance programs. Figure 4 below represents the Proposed timeline and strategies for successful timber construction adoption in Sri Lanka.

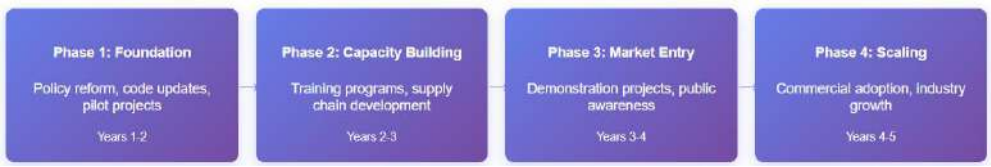

Figure 19- Strategic Implementation Roadmap

6. LIMITATIONS

Despite the valuable insights generated by the study, several shortcomings must be pointed out. In terms of methodology, the quantitative survey's small sample size (n=20) and limited geographical spread makes the findings difficult to generalize, while the qualitative insights may be rich, they only reflect the views of a small number of industry professionals and the overall opinions within the industry may be much broader.

Given the nature of the research, it was conducted in a setting with considerable regulatory gaps and a lack of baseline data on the local timber properties which

negatively impacted some aspects of the feasibility analysis. Additionally, the study describes, but cannot fully tackle, the issue of a cultural bias towards concrete which was identified as a major barrier. The issues noted above could be addressed in future research by using more diverse and larger samples as well as longitudinal designs in order to validate and build on the findings of the study.

7. CONCLUSION

This comprehensive study demonstrates that timber-based residential construction represents a viable and sustainable alternative for Sri Lanka's housing sector, offering significant environmental, economic, and social benefits. The research reveals strong foundational support with 90% public awareness of timber's construction potential and 80% willingness to consider timber-based housing, indicating market readiness for sustainable construction alternatives.

Important findings verify timber's exceptional environmental performance with reduced carbon footprint, lower greenhouse gas emissions, and higher energy efficiency than traditional concrete and steel building construction. Advanced engineered wood products, such CLT and GLT, in concert with prefabrication technology, provide superior building construction efficiency, lower labour intensity, and increased quality assurance. Energy-efficient building suitability in Sri Lanka's climate with thermal performance benefits and inherent natural insulation verify these findings.

But important systemic obstacles now prevent widespread adoption. Preferences for concrete construction due to notions of modernity and permanence need specialized education and demonstration efforts. Technical issues consist of poor building codes, scarce professional experience, inadequate regulatory direction, and immature supply chains. Skills mismatches permeate the entire construction value chain, across site manpower to professional expertise, and so require complete workforce development strategies.

Resource assessment indicates high potential through local diversity of species and potential for plantation development, although existing supply chains are patchy and systems of quality control insufficient. Widespread structural use of timber in non-structural applications such as roofing, door and window applications indicates comfort with timber characteristics while presenting opportunities for increased structural uses.

Economic reasoning finds adoption choices to be very sensitive to cost, with 60% of the respondents in our study planning to adopt timber construction if 10-20% cheaper than traditional solutions. This suggests that cost advantage based on mass production, greater efficiency, and optimized supply chain could expedite market entry.

These findings point to a clear mainstreaming route of timber construction via product reform through coordinated policy, regulatory up-dating, professional development, and public education programs. Government advocacy stands out significantly, with 95% in favor of timber construction if affordable and sustainable, although 45% still have doubts regarding due levels of government intervention, which calls for transparent communication of policy and involvement of stakeholders.

Expert opinions stress the significance of holistic solutions overcoming cultural, technical, regulatory, and economical obstacles at the same time. Adoption of timber becomes successful through combinations of traditional knowledge and contemporary

engineering potential in light of thorough training modules, new building codes, and pilot projects demonstrating practical viability.

Studies sum up that Sri Lanka has the very prerequisites of successful timber-based residential construction in place: sufficient resource potential, expanding environmental awareness, foundation of technical capability, and conditional public approval. But the attainment of this potential involves concerted efforts in all the spheres of policy building, industry capability development, manpower training, and public communication.

With suitable strategic measures, timber has the potential to become a foundation of Sri Lanka's future sustainable housing, supporting mitigation of climate change, economic growth, and enhancing the living standards. Blending between the timber construction advantages and the country's sustainability targets and rising international focus on low-carbon development makes timber suitable to act as a strategic material in the transformation of Sri Lanka's construction sector.

This study provides the foundation from which to develop evidenced-based policies and industry planning to steer Sri Lanka toward sustainable building construction practices in line with international climatic targets and domestic development agendas. Implementation strategies, performance-monitoring systems, and continuous improvement systems ought to be the focus of future research to ensure successful incorporation of timber building in Sri Lanka's evolving building industry

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POSTER SESSION

Development of an AI-Driven Trading Bot for XAU Using Sentiment Analysis and LSTM Models

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Abstract—Presented in this paper is the challenging task of building a profitable, risk-management-focused automated trading system for the volatile gold market, which can be generalized to the forex market. It is argued that the failure of mono-modal trading models necessitates a multi-modal approach. The main system, based on a Long Short-Term Memory (LSTM) network and augmented by technical and external market data, is managed by a deterministic, rule-based execution logic. This system demonstrated significant profitability in comprehensive 5-year back-testing (2020-2025), turning a $1,000 deposit into $75,277 ($74,277 profit). Following this, forward testing (April 1-22, 2025) achieved $8,638 from $1,000 in 22 days, and a successful one-month live test generated approximately $1,678 profit. As the primary predictive method is aggressive, a secondary model, or "brain" of the system, was developed as an optional submodule using a Deep Q-Network (DQN) Reinforcement Learning agent. This agent, while more risk-averse, achieved a consistent Sharpe Ratio of 3.40, demonstrating its potential as a complementary tool for risk monitoring. Ultimately, this study demonstrates the viability of dual architecture, with its characteristics dictating its operational mode.

Keywords—AI-Driven Trading, Sentiment Analysis, LSTM, XAU, ML

ML-Based Loan repayment default prediction system for improving credit risk assessment in the banking industry

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Abstract— This research aims to address the critical challenge of loan default prediction within the banking sector, aiming to enhance the accuracy of credit risk assessments. The lending process is one of the most important parts of the banking sector. Current systems in the banks struggle with rapidly changing data, leading to lower accuracy in real-world applications. Also, the current system does not use Machine Learning algorithms to predict the data. To overcome these limitations, this study employs a machine learning approach to develop a loan default prediction system, specifically focusing on the main two types of loans like Personal and Housing loans. A loan default is identified based on overdue days exceeding 90 days, as per the bank's system. So, the primary objectives are to analyze the machine Learning algorithms and develop predictive models for each loan type using machine learning algorithms and to design a user-friendly data product for predicting loan default status. However, this study holds substantial importance for banking institutions by improving their ability to predict loan defaults, providing a more detailed and precise evaluation of each loan's probability of default by integrating financial borrower behavior, such as average savings account balances. Also, this system can predict the borrower's repayment pattern and predict the loan default of the borrower. So, the predictive model aims to enable banks to make informed lending decisions, thereby reducing high-risk loans and strengthening overall financial stability.

Keywords—Machine Learning, Housing Loan, Personal Loan, ML Algorithms

A BERT-Based Model for Determining University Students' Non-Clinical Academic Difficulties

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Abstract : Academic issues like procrastination, poor time management, high stress, and low mindfulness often compromise university students' academic outcomes. These concerns, though non-clinical, can profoundly influence academic achievement and personal growth. This work presents a BERT-based classifier specially trained to detect such non-clinical academic issues via student-generated text data. A synthetic dataset comprising 50,000 utterances was created to mimic real-world student concerns, enabling intense model training while maintaining privacy and ethical requirements. Although a small set of anonymized student responses was collected for qualitative reference, it was not used in training or evaluation due to privacy and data volume limitations. With state-of-the art training strategies, including gradient checkpointing, class weighting, and automatic mixed precision, the fine-tuned BERT classifier attained a validation accuracy of 92.3% and F1-score of 0.91. This outcome showcases BERT's ability to differentiate subtle psychological states in non-clinical contexts. The suggested approach provides a scalable, privacy-friendly, and explainable basis for personalized academic support platforms, especially in university settings where students avoid seeking professional assistance. This work contributes to AI-driven educational technology and facilitates the development of adaptive, non-clinical student well-being interventions in the future.

Keywords: Academic procrastination, BERT Model, Mindfulness, Non-clinical support, Time management.

Shortest Path Analysis of Tourist Routes in Sri Lanka Using Dijkstra's Algorithm

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Abstract—Sri Lanka's dispersed and varied tourist attractions necessitate optimal trip planning for travelers who want to visit more than one destination within time and budget limitations. This paper introduces an intelligent route planning scheme that employs Dijkstra's algorithm to calculate the most efficient and shortest routes of travel between chosen tourist destinations in Sri Lanka. By mapping attractions and highways as a weighted graph, the system calculates optimal routes to help visitors minimize travel time and transportation costs. For improved practical applicability, the solution may use real-world map data by consuming the Google Maps API for accurate distance computation and dynamic route optimization. The proposed approach facilitates smart tourism development by combining conventional graph algorithms with novel location-based services and provides tourists with convenient, low-cost, and time-saving tours.

Keywords—Dijkstra's Algorithm, Google Maps API, Python, Shortest Path, Smart Tourism, Sri Lanka, Travel Itinerary Optimization, Graph Theory, Navigation System.

Guide Cap: Enhancing Mobility and Awareness through Embedded Tech

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Abstract—This paper introduces the Guide Cap, a new wearable assistive technology to promote mobility and situation awareness in the visually impaired. It integrates an ultrasonic sensor with real-time object detection, a DFPlayer Mini to give audible feedback, and a DS3231 RTC module to declare time. A NEO-6M GPS module allows accurate location and time synchronization, while a solar battery extends operating time and allows for extended use. All the components are governed by a single ESP32 microcontroller, eliminating the need for multiple controllers and making the system more efficient. Trial experiments determined a stable detection distance of 15–200 cm with an overall accuracy of 92% and response time of below 150 ms. Power consumption ranged from 1.1 to 3.0 W, providing a 3–8-hour battery life under typical conditions. By combining GPS, RTC, and ultrasonic sensing in a compact, affordable package, the Guide Cap is a handy, low-energy, and green mobility aid and contributes to the growing market of smart assistive technologies.

Keywords— Assistive technology, obstacle detection, wearable devices, ESP32, solar-powered system.

Energy Management of Hybrid Energy Storage Systems using Lithium Iron Phosphate and Lithium-Ion Batteries for Wind Power Systems

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Abstract—This study investigates the integration of Hybrid Energy Storage Systems (HESS) with wind power plants to enhance grid stability and improve the dynamic response of renewable energy systems. The proposed HESS architecture combines two complementary storage technologies: a High Energy Storage (HES) unit typically a Lithium-based battery for sustained energy supply—and an Instantaneous Power Storage (IIPS) unit designed for rapid compensation of power fluctuations. The research evaluates two battery chemistries, Lithium Iron Phosphate ($LiFePO_4$) and Lithium-Ion, through detailed life cycle assessment, dynamic degradation modeling, and lifetime prediction to determine their suitability for HESS applications. A comprehensive mathematical model of the HESS is developed, incorporating an adaptive energy management algorithm that dynamically allocates power between the HES and IIPS units based on system demands. The study addresses a critical gap in existing literature by emphasizing the long-term performance and sustainability of hybrid storage configurations in wind-integrated power systems. Key objectives include analyzing current HES and IIPS technologies, formulating a robust hybrid energy management strategy, and quantifying the impact of HESS on system reliability and battery longevity. Simulation results demonstrate that the hybridization of energy storage significantly enhances the techno-economic performance of wind energy systems. The proposed HESS not only mitigates power imbalances but also supports ancillary services such as frequency and voltage regulation. The findings underscore the potential of HESS to serve as a reliable and sustainable solution for integrating intermittent renewable energy sources into modern power grids.

Keywords—Hybrid Energy Storage Systems (HESS), Wind Power Integration, Battery Life Cycle Analysis, Energy Management Algorithm, Grid Stability and Ancillary Services

Voltage Unbalance Mitigation in Three-Phase PV-Integrated Distribution Networks Using Battery Energy Storage Systems

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Abstract—With the escalating use of rooftop solar photovoltaic systems in low-voltage distribution networks, there arise new challenges for voltage stability and power quality. Single-phase and three-phase types of PV inverters are used in Sri Lanka by both residential and commercial consumers. Sometimes the uneven distribution of PV inverters among phases and capacity variations of inverters and solar irradiance results in unbalanced power injection in the grid. This causes voltage magnitude unbalance and eventually increases the Voltage Unbalance Factor, which becomes detrimental to sensitive equipment and to the reliability of an overall network. This paper assesses the impact of such unbalanced PV integration in a three-phase radial distribution network and presents a solution via a grid-connected Battery Energy Storage System. Following the proposed approach, the BESS would be able to inject or absorb active power on a per-phase basis according to the real-time voltage measures to keep voltages within acceptable limits and reduce the VUF. To assess the effectiveness of the proposed controller, a MATLAB/Simulink model is developed to represent plausible variability in PV generation and inverter configurations. From the results, BESS shows improvements of voltage symmetry and system performance to hold its claim as one of best control solutions for voltage unbalance mitigation in PV-integrated distribution networks.

Keywords—Voltage Unbalance Factor, Battery Energy Storage System, PV-Integrated Distribution Network, Per-Phase Power Control, Voltage Stability

Modelling and Simulation of Demand-Side Load Management Strategies

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Abstract- Rising global energy demands and electrical infrastructure facing growing pressure, efficient Demand-Side Load Management (DSLM) is crucial for modern power systems. In this research, two significant DSLM techniques, load shedding and peak clipping, are developed and simulated using MATLAB Simulink. The load shedding simulation classifies the loads as critical and non-critical and selectively sheds non-critical loads when demand exceeds a predetermined value, thus sustaining critical services and preventing system overloading. The peak clipping method applies upper and lower limits to power demand to reduce the peak-to-average load ratio and flatten demand profiles. Time-series data was used to simulate a 10-hour load profile with limited system capacities. The results confirm that the two methods help in energy optimization, grid reliability, and reduced infrastructure stress. This study addresses significant gaps in literature by utilizing realistic simulations with categorized loads and static thresholds, laying the groundwork for integration with upcoming smart grid and AI-based systems.

Keywords—Demand-Side Load Management, MATLAB Simulink, load shedding, peak clipping, Energy Optimization, Global energy demand

Optimizing Flywheel-Hydrogen Energy Storage for Large-Scale Renewable Integration

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Abstract—Increasing penetration of intermittent renewable sources of energy solar, complicates maintaining grid stability and matching supply with fluctuating demand. To solve this problem, this research proposes the design and optimization of a hybrid flywheel-hydrogen energy storage system consisting of short-term, high-power flywheel storage and long-term hydrogen fuel cell storage. System sizing, load balancing, and efficiency are modeled using a MATLAB-based simulation environment. Optimization seeks to minimize the reliance on fuel cells, increase the responsiveness of the system, and ensure the stable provision of energy. Preliminary results show that integration with flywheels lowers the demand for fuel cells and enhances load-following. Flywheel operation parasitic losses render PV and electrolyzer capacities greater than required. The study also cites some of the research areas of immediate importance, such as scalability to grid-scale applications, a comparison of hybrid systems with other systems (e.g., battery-hydrogen, supercapacitor-fuel cell), and transient load behavior in dynamic situations. Lastly, this study hopes to contribute to the formation of robust, efficient, and scalable energy storage devices toward a sustainable future for renewable energy.

Keywords—Flywheel, Hydrogen, Optimization, Renewable energy

Design and Development of an Eye Gesture Controlled Adaptive Wheelchair System Using Advance Machine Learning Techniques

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Abstract: AMillions of individuals worldwide are paralyzed and use manual wheelchairs but are not in a position to operate them independently without any outside help. They might lose their independence and mobility, which can profoundly impact their quality of life. This project introduces a full electric wheelchair kit that transforms manual wheelchairs into electric wheelchairs and can be controlled with the user's eyes. This system is intended for individuals with complete paralysis who can only operate it using their eyes but is also accessible for non-paralyzed individuals who want to leverage the features of an electric wheelchair. Unlike other costly eye- controlled wheelchairs that involve the use of manual wheelchairs, therefore taking away the manual wheelchair from the user, our solution offers a low-cost conversion kit that preserves the original wheelchair's structure. Customized eye gesture recognition for different patient needs is achieved by using computer vision and deep learning algorithms. Experimental results demonstrate successful implementation with easy setup and reproducible outcome for different groups of users.

Key words *— Electric wheelchair, Eye gestures, Paralysis, Convertible*

A Review of Real-Time Intelligent Traffic Light Control Systems: Bridging Gaps with Multi-Camera GPU-Accelerated YOLO for Heterogeneous Traffic

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Abstract — This paper presents a critical review of existing intelligent traffic light control systems, advanced computer vision techniques, and You Only Look Once (YOLO) object detection applications. It highlights the identified research gap concerning the integrated application of multi-camera parallel processing, GPU-accelerated frame processing, and fine-tuned YOLO models for real-time three-wheeler detection in the context of intelligent traffic light control. The paper concludes by discussing the significance of addressing this gap for enhancing urban mobility and safety in heterogeneous traffic environments. A notable study introduced a multi-camera YOLOv8-based real-time system incorporating GPU acceleration and a dedicated three-wheeler dataset, achieving competitive mAP scores with efficient identity tracking across cameras. This method also addressed viewpoint variance, occlusion, and heterogeneous traffic conditions by deploying parallel frame processing pipelines using Jetson Orin devices for edge inference [1] Recent advancements in bridge traffic monitoring have emphasized the value of vision-based systems. Previous work introduced an open-source dataset specialized for vision-based traffic load monitoring on cable-stay bridges. This benchmark dataset includes over 32,000 annotated images, calibration data, and synchronized video-WIM recordings, enabling deep learning model training and validation in real bridge environments. The dataset supports accurate spatial load distribution estimation and encourages further development of bridge traffic analysis technologies [2].

Keywords — Computer Vision, Deep Learning, GPU Acceleration, Intelligent Traffic Signal Control (ITSC), Multi-Camera Systems, Real-Time Video Processing, YOLO Object Detection.

A Comprehensive Review of Intelligent Control Techniques for Evaporation Systems in Process Industries

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Abstract — Evaporation systems, such as multi-effect evaporators in sugar, ethanol, and food processing, are energy-intensive units whose performance directly impacts product quality and operating cost. Intelligent control strategies have evolved to tackle the challenges posed by these systems' nonlinear dynamics, long dead times, and strong inter-effect couplings. This paper presents a comprehensive IEEE-style review of advanced control techniques for industrial evaporation processes, focusing on Fuzzy Logic Controllers (FLC), Artificial Neural Networks (ANN), Adaptive Neuro-Fuzzy Inference Systems (ANFIS), Model Predictive Control (MPC), and Reinforcement Learning (RL). The evolution, applications, and comparative performance of these methods are examined. Key findings indicate that fuzzy controllers improve stability and interpretability over traditional PID control, ANN/ANFIS models enhance predictive accuracy for complex evaporator behavior, MPC provides effective multivariable constraint handling and can optimize steam economy, and RL-based controllers show promise in self-optimizing evaporator operation. Energy optimization is a unifying theme: intelligent controllers consistently demonstrate better steam usage and reduced operational costs. Identified gaps (such as scalability to multi-effect systems and interpretability of AI models) and emerging trends (like hybrid MPC-RL approaches and explainable AI for process control) are also discussed. The insights from this review highlight the most effective techniques and future directions for intelligent evaporator control in process industries.

Keywords — Adaptive control, Artificial neural networks, Evaporator systems, Fuzzy logic control, Intelligent process control, Model predictive control, Reinforcement learning.

Internet of Things in Mechatronics: Architectures, Protocols, and Applications

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Abstract— The Internet of Things (IoT) refers to a paradigm of networked smart devices equipped with sensors and actuators communicating to serve meaningful purposes. This paper provides a foundational overview of IoT in the context of mechatronics, highlighting the historical evolution of the field, core architectural frameworks, key communication protocols, and representative applications. Emphasis is on how IoT principles are framed within mechatronic system design, offering an undergraduate-level introduction with essential technical insights.

Keywords— Internet of Things (IoT); Mechatronics; IoT Architecture; Communication Protocols; Smart Devices; Industrial IoT.

Exploration Of How Social Roles And Status Influenced The Anthropometric Design Of Wooden Chairs In The Kandyan Period Of Sri Lanka

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Abstract— This study explores how social roles and status influenced the design and anthropometric features of wooden chairs during the Kandyan Period of Sri Lanka. By integrating qualitative and quantitative research methods, the investigation examines how chair dimensions, materials, symbolic motifs, and craftsmanship practices reflected the sociocultural hierarchy of the time. Data was collected through literature review, case studies, direct observation, photographic surveys, and manual measurements of chairs found in museums and temples. The findings reveal that furniture served not only functional but symbolic roles distinguishing royalty, clergy, and nobility through size, elevation, and intricate carvings, while commoners used simple floor-level seating. Anthropometric analysis shows that chair dimensions varied by user status, with royal and noble chairs often exceeding modern ergonomic norms, emphasizing formality and authority over comfort. These traditional proportions were compared to contemporary ergonomic standards from references such as Neufert's Architects' Data and Human Dimensions and Interior Space, offering insights into the cultural and functional logic behind historical design. The study contributes to the understanding of traditional craftsmanship, spatial hierarchy, and ergonomic relevance, offering valuable perspectives for interior design, heritage conservation, and culturally inspired furniture design today.

Key words : *Kandyan Period, Wooden Chairs, Social Hierarchy, Anthropometry*

Explore the virtual reality adaptation in the Sri Lankan interior design industry

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Abstract— The interior design industry in Sri Lanka is gradually adopting Virtual Reality (VR) to enhance design visualization, communication, and client engagement. While VR demonstrates strong potential to transform the design process by improving spatial understanding and reducing misunderstandings, its widespread implementation remains limited due to high costs, insufficient technical knowledge, and restricted access to advanced technology. Emerging applications such as virtual walkthroughs and cultural heritage visualizations further highlight VR's growing relevance in the field. Local firms, including Nex–Gen Engineering Studio, TDK Architects, and COD Studio, are actively integrating VR, Building Information Modeling (BIM), and 3D visualization into their workflows, contributing to the development of digital design practices in Sri Lanka. Clients who experience VR-based presentations report increased satisfaction and confidence in decision-making. As infrastructure and professional awareness continue to improve, VR is expected to play a crucial role in shaping a more efficient, collaborative, and client-centred future for interior design in Sri Lanka.

Key words : *Virtual Reality, Sri Lankan, Interior Design Industry*

The Impact of Digital Tools On Enhancing Carpentry Work in Furniture Manufacturing

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Abstract — This research explores the impact of digital tools on enhancing carpentry work in furniture manufacturing, with a focus on understanding how modern technologies are being adopted and integrated into the traditional carpentry process. The study was conducted among 24 participants from three selected furniture manufacturing companies (Dark Gray Piliyandala, Monara Creations, and Leema Creations) representing different levels of digital tool integration. Participants included carpenters, interior designers, and project managers. The research specifically investigates the usage, benefits, challenges, and perceptions of digital tools, including CNC machines, CAD software, and other computer-aided technologies. These tools are increasingly influencing design accuracy, production efficiency, and creativity in the furniture-making process. A structured questionnaire with 25 closed-ended questions and an on-site observational study (documented through machine photographs and descriptions) were used to collect data. The analysis was conducted using pie charts for demographic data and bar charts for the sections: tool usage, benefits and creativity, challenges, and perceptions and suggestions. Findings revealed that most participants recognized the benefits of digital tools in enhancing both the quality and speed of production. However, challenges such as a lack of training, high initial investment, and resistance to change were also identified. The study contributes to a better understanding of how digital transformation is shaping the future of carpentry-based furniture manufacturing in Sri Lanka and suggests practical recommendations to improve digital tool adoption in the industry.

Keywords — Digital tools, Carpentry work, Furniture manufacturing, CNC machines, CAD software, Technological integration

The Impact of Sri Lankan Batik Materials on Durability in Interior Applications Of The Hotel Industry

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Abstract—This research investigates the impact of Sri Lankan batik materials on durability in interior applications within the hotel industry. While batik offers cultural richness and aesthetic appeal, its performance under high traffic, commercial hospitality conditions have been largely unexamined. This study evaluates the durability of batik through testing (wash cycles, rub resistance, and UV exposure) on super voile fabric to assess its suitability for practical interior use. Key objectives include: To analyse the durability of Sri Lankan batik fabrics when used in various hotel interior applications such as upholstery, wall coverings, curtains, and decorative elements. To examine the traditional production methods and cultural relevance of Sri Lankan batik as a foundation for its integration into interior design applications. To identify the key factors affecting the longevity of batik materials in hotel settings, including exposure to sunlight, dye bleeding, shrinkage, and other fabric degradation processes. The study combines experimental data, and precedent analysis to establish a comprehensive understanding of batik's viability in modern hospitality design. Results suggest that with careful application, Sri Lankan batik can function as both a decorative and durable material in specific interior contexts, particularly in low-contact and shaded zones. This research contributes to sustainable design strategies while preserving and promoting traditional Sri Lankan craftsmanship.

Keywords—Sri Lankan Batik, hotel interiors, fabric durability, interior application

Exploring The Role of Furniture Arrangement in Co Working Interior Spaces in Enhancing Productivity

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Abstract- This study explores how furniture arrangement in co-working interior spaces influences user productivity, collaboration, and satisfaction. Using a mixed-methods approach, data were collected from three co-working spaces in Colombo—Rezg Hub, Connect Co-working, and Likuid Spaces—through surveys, interviews, and observations. Findings reveal that well-planned furniture layouts, including flexible seating, open work zones, and private booths, enhance user focus, communication, and work efficiency. The research shows that spatial flexibility and ergonomic comfort directly impact how individuals perform in shared environments. Both international and Sri Lankan perspectives highlight that thoughtful furniture design not only supports different work styles but also fosters a sense of community. The study concludes that interior layout is a critical factor in improving productivity within co-working spaces and offers recommendations for design professionals and space managers..

Keywords - Co working spaces , Interior ,Furniture arrangement , productivity

The Effect of Integrating Nature-Inspired Concepts on Productivity and Functionality in Design Studios

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Abstract: This study investigates ways in which the intersection of nature-inspired concepts biophilia, sustainability, and biomimicry can be applied to enhance productivity and performance in interior design studios. Because studios demand high levels of creativity and concentration, the built environment must support physical as well as psychological comfort. The ultimate objective is to operationalize the quantifiable effects of natural design elements on designer performance and describe how it can be done in the future. Literature suggests that nature element like light, leaves, and natural material Support cognitive restoration, emotional stability, and ergonomic efficiency. Case studies of two Sri Lankan design studios reveal the application of biophilic principles in practice in spatial performance design. The study entailed the use of the qualitative method approach through the combination of the structured questionnaire and visual examination. The data analysis concluded that natural characteristics were strongly related to boosted creativity, teamwork, and focus. Overall, the use of nature-drawn concepts produces healthier, stronger studios for greater user satisfaction and overall design performance.

Keywords: *Nature Inspired concepts, productivity, functionality, design studio*

An Evaluating User Behavior and The Effectiveness of Antimicrobial Materials In Interior Design of Hotels In The Galle District In Mitigating COVID-19 Transmission Risks

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Abstract - The pandemic caused by COVID-19 has served to underscore the significance of surface material selection and hygiene in public environments, such as in hospitality. This research evaluates the influence of antimicrobial materials and user behavir on the transmission of COVID-19 in hotel interiors in the Galle District, Sri Lanka. Informed by a qualitative case study approach, seven hotels (3 to 5 stars) were surveyed with the help of photographic surveys, observational studies, and material audits in high-contact zones receptions, lobbies, and restaurant premises. Findings reveal heavy reliance on germ-collecting materials wood, cane, and cloth, with minimal uptake of antimicrobial treatments. While some such as glass and ceramic tiles were hygienically beneficial, user practices (eg, inadequate hand washing and uncontrolled contact) nullified their efficacy. Hotels are Rock Fort and Amanda Beach Villa reflected moderate uptake of design-driven measures (washable surfaces, ventilation), but overall, systematic infection control mechanisms did not exist. The study concludes that without combining material-based hygiene with behavir conscious design strategies, infection prevention in hotel interior spaces remains poor. The findings justify implementing a combined strategy to interior design that combines the utilization of antimicrobial materials, behavir cues, and adherence to World Health Organization (WHO), Centers for Disease Control and Prevention.(CDC) recommendations.

Keywords- Antimicrobial Materials, COVID-19, Surface Hygiene, Hospitality Design, User Behavior, Germ-Collecting Materials

The Role of Reused Steel in Modern Commercial Interior Design: Case Studies and Applications

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Abstract - This paper explores the role of reused steel in shaping sustainable commercial interior design practices in Sri Lanka. It investigates how repurposed materials influence both functionality and aesthetics, emphasizing their environmental and economic benefits. Using mixed methods—professional surveys, interviews, and visual analysis—data were collected from 30 design professionals and three case studies (NC Lounge, Café Keku, and The Paint Shop). Findings reveal that 73.3% of professionals have used reused steel, valuing sustainability (43.3%) and cost-efficiency (36.7%). Challenges such as inconsistent supply (65%) and quality concerns (48%) persist, yet creative design solutions demonstrate reused steel's adaptability and visual appeal. This study concludes that reused steel is an eco-friendly material with high potential for commercial interiors when supported by better sourcing, standards, and education.

Keywords - Reused Steel, Sustainable Design, Interior Design, Material Reuse, Sri Lanka

Analyzing a blind comparative study on the user perception of Human design vs AI generated interiors within a residential space in Colombo

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Abstract— The accelerating integration of Artificial Intelligence (AI) into creative disciplines demands a deeper understanding of its impact on established design practices. This research explores how professional interior designers perceive AI-generated compared to human-designed bedroom layouts, aiming to evaluate effectiveness, user preferences, and the evolving role of AI tools in contemporary design. Using a blind comparative methodology, ten industry professionals assessed four-bedroom interiors, two created by humans and two with the help of AI, without knowing their origins. Evaluations focused on comfort, spatial logic, aesthetic appeal, functionality, and privacy, employing quantitative feedback to capture both preference trends and underlying reasoning. Findings highlight AI's value as a complementary tool, demonstrating efficiency and consistency while emphasizing the continued importance of human contextual understanding and empathy. The study advocates hybrid workflows that integrate AI's analytical precision with human creativity to enhance design outcomes. Acknowledging limitations such as the small sample size and reliance on a single AI platform, it recommends future studies involving multiple AI tools and broader design applications. This work provides clear evidence of AI's capabilities and constraints in interior design, contributing valuable insights into fostering effective human-AI collaboration within the industry.

Keywords—Blind comparative study, User perception, Human designed interiors, AI-generated interiors, Residential space

Comparing The Impact of Traditional Drafting And Digital Drafting on Design Outcome in Interior Design Education at NSBM Green University

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***Abstract*—**Rapid technological advancements are causing a shift in the tools and techniques used in interior design education. The purpose of this study is to compare how NSBM Green University interior design students' design outcomes are affected by traditional drafting and digital software tools. The literature review highlights how digital tools improve accuracy, efficiency, and visual communication, while traditional drafting grows fundamental manual skills and design thinking. It also highlights the increasing need of matching professional design industry demands with academic training. Examining how each approach affects students' design development, learning process, and creative output, as well as how these methods aid in the overall design process and skill acquisition, is the goal of this study. Qualitative data were gathered using a comparative methodology that included surveys and an assessment of student projects. Through the analysis of survey responses and the assessment of finished interior design projects, this method offered helpful data about the preferences, experiences, and design outcomes of students. Results show that while traditional approaches enhance manual dexterity and concept development, digital software greatly increases accuracy, time management, and flexibility. The study comes to the conclusion that using both approaches into the curriculum offers an efficient and complete approach to teaching interior design.

Key words: *Traditional drafting, Digital drafting, Design outcome*

Impact of tactile features on sensory cues of visually impaired patients at National Eye Hospital, Sri Lanka

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Abstract—A visually impaired person's eyesight cannot be corrected to normal levels. They heavily rely on their other senses more than the visual sense to understand their surroundings. Tactile features cater to the haptic cues of a visually impaired person through helping with tactile navigation & way finding, safety & hazard awareness, independence & self-awareness, communication & information access & spatial orientation & memory. This study is conducted to explore the sensory cues of visually impaired patients & how they can be catered using different tactile features, materials, lighting & colours. Also, the existing tactile features are identified along with the influence tactile features have on visually impaired patients at the National Eye Hospital Sri Lanka. A mix method (qualitative & quantitative) study is carried out through a comprehensive literature review, observational study & questionnaire surveys. The Outpatient Department of the National Eye Hospital is chosen for the study as it's the tertiary care centre for the visually impaired patients in Sri Lanka. Visually impaired patients & staff members from the General Ophthalmology Clinics were chosen for the study. This study clearly shows that the existing tactile features are not sufficient for the visually impaired patients. Overall, most of the staff members think that implementing tactile features will be beneficial for the patients while almost 50% of the patients agreed with them. Finally, this research clearly depicts the importance of implementing tactile features in the Outpatient Department of the National Eye Hospital.

Keywords—Tactile features, sensory cues, visually impaired patients, National Eye Hospital, Sri Lanka

Evaluating The Thermal Efficiency and Aesthetic Qualities of Rice Husk Based Clay Wall Panel for Sustainable Building Application

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Abstract— This study evaluates the thermal performance and aesthetic characteristics of lightweight wall panels produced from rice husk–reinforced clay for sustainable building applications. A locally sourced clay mixture known as "Goda Meti", a traditional Sri Lankan blend of clay and natural additives used in construction, was selected based on preliminary trials. The clay underwent sun-drying for seven days, grinding into powder, and removal of non-clay particles before paste formation. Rice husk was incorporated at concentrations ranging from 10 to 20 weight percent (wt%). The addition of 15 wt% rice husk resulted in the greatest improvement in thermal insulation, reducing the temperature gradient by -0.10°C/mm compared to pure clay. Increasing rice husk content beyond 15 wt% produced negligible further changes. Higher rice husk content decreased bulk density from 1.52 to 1.10g/cm3, increased water absorption, and did not significantly affect thickness swelling. Assessment of surface color, texture, and smoothness identified the most favorable aesthetic finish at 10 wt% rice husks. Lastly, rice husk–Goda Meti clay panels demonstrate reduced weight and improved thermal insulation with acceptable surface quality, supporting their potential as low-cost, sustainable interior wall panels for energy-efficient buildings.

Keywords—Rice Husk, Clay, Sustainable Wall Panel, Thermal Conductivity, Aesthetics Qualities

The Role of Nanomaterials in the Evolution of Additive Manufacturing

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Abstract— Additive manufacturing (AM), also known as 3D printing, builds parts layer by layer from digital models. In recent years, the use of nanomaterial structures with features between 1 and 100 nanometers has significantly advanced this technology. Nanomaterials such as carbon nanotubes (CNTs), graphene, metal and ceramic nanoparticles, and Nano clays offer mechanical, thermal, electrical, and chemical properties that traditional materials do not offer. On their incorporation into AM feedstocks, these nanomaterials can enhance printed parts by achieving greater strength, stiffness as well as durability and by imparting new functionalities such as electrical conductivity, thermal management or even being able to live. This review outlines the benefits of nanomaterials on various AM processes, such as Fused Deposition Modeling (FDM) and Stereolithography (SLA) and Powder Bed Fusion (PBF). It points out that recent years bring strong nanocomposite filaments, nano-reinforced resins, and nano-coated metallic powders (graphene), which increase part density and performance. Other applications and use in practice are also mentioned, including lightweight structural components in the aerospace industry, personalized implants in the field of medicine, electronic printing in wearable electronics, and intelligent components in constructions. The most crucial limitations such as nanoparticle dispersion, printers' compatibility, cost, and safety regulations are solved. Lastly, some future avenues including smart nanocomposites, multi-material printing, bio-based fillers, and process optimization using AI are discussed. This paper intends to offer a brief and definitive survey to the researchers and engineers that would like to familiarize themselves with the synergy between nanotechnology and additive manufacturing.

Keywords— Additive Manufacturing (AM), Nanomaterials, 3D Printing, Nanocomposites, Fused Deposition Modeling (FDM), Stereolithography (SLA), Powder Bed Fusion (PBF)